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(NASA-CR-169626) RF MODEL OF THE  
DISTRIBUTION SYSTEM AS A COMMUNICATION  
CHANNEL, PHASE 2. VOLUME I: SUMMARY REPORT  
Final Report (General Electric Co.) 119 p  
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## RF MODEL OF THE DISTRIBUTION SYSTEM AS A COMMUNICATION CHANNEL

### PHASE II

### VOLUME I — SUMMARY REPORT

FINAL REPORT  
Contract No. 955647

July 28, 1982

R.C. Rustay  
J.T. Gajjar  
R.W. Rankin  
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Prepared for

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4800 Oak Grove Drive  
Pasadena, California 91103

SRD-82-055-1

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This work was performed for the Jet Propulsion Laboratory, California Institute of Technology sponsored by the U.S. Department of Energy, through an agreement with the National Aeronautics and Space Administration.

SRD-82-055-1

## ABSTRACT

This four-volume final report is concerned with Phase II of the DOE/JPL project "RF Model of the Distribution System As a Communication Channel." An earlier Phase I effort was concerned with the design, implementation, and verification of a computerized model for predicting the steady-state sinusoidal response of radial (tree) configured distribution feeders. That work demonstrated the feasibility and validity based on verification measurements made on a limited size portion of an actual live feeder. The Phase II effort is concerned with 1) extending the verification based on a greater variety of situations and network size, 2) extending the model capabilities for reverse direction propagation, 3) investigating parameter sensitivities, 4) improving transformer models, and 5) investigating procedures/fixes for ameliorating propagation "trouble spots."

#### STATEMENT ON NEW TECHNOLOGY

During the performance of the work on this Phase II, no reportable items of new technology have been identified.

## PREFACE

This volume contains a summary of the Phase II work. \_

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A. FOREWORD

This volume attempts to present an overview-summary of the background work, status, and conclusions associated with the completion of the PHASE II effort and is directed to readers who do not have the need or desire to study the more detailed aspects as reported in the other volumes of this series. In the event the reader has not had access or opportunity to read the Volume 2 - Summary associated with the PHASE I work, a (slightly edited) copy of a "Tutorial Overview to Modeling Feeder Network For PLC\* Propagation" has been included, for their reference, as the last section of this volume. For further details, the reader is referred to the PHASE I final reports subject.

\*PLC - Power Line Carrier



## B. PURPOSE

The primary purpose of the earlier and completed PHASE I effort was to develop, implement, and verify against measurements, a model to determine the feasibility of predicting, via the model, the propagation of Power Line Frequency (PLC) on radial type distribution feeders. Since emphasis was to determine feasibility (at that time unknown) the approach was taken to avoid making any more engineering assumptions in the modeling than necessary and to intentionally choose a test circuit which was physically long enough to exhibit standing wave phenomenon, but otherwise, as little encumbered as possible with confounding complexities. (See Section H of this report). Comparing model predictions with measurements made on this "ideal" (but real) test circuit, it was concluded that it was potentially feasible to predict PLC propagation with sufficient accuracy to be useful for PLC communication purposes.

On the basis of having established an initial feasibility in PHASE I, the primary purpose of the PHASE II follow-on was to continue the verification activity, comparing model predictions against measurements, using more complicated feeder circuits and situations. Also included as secondary objectives were:

Continue development and application of exact "perturbation" procedures for the calculation of reverse direction propagation.

Investigate parameter sensitivities and procedures of reducing "set-up" time for modelling.

Continue Transformer Modeling

Investigate procedures/fixes for ameliorating  
propagation "trouble spots".

The specific details of these PHASE II objectives are contained  
in Section D of this volume which presents the PHASE II contract  
work statement.

### C. HISTORICAL BACKGROUND

The earlier and completed PHASE I began in May, 1977 after award of an ERDA RFP2100 entitled:

RF MODEL OF THE DISTRIBUTION SYSTEM AS A  
COMMUNICATION CHANNEL

Contract No. EC-77-C-01-2100

and under the technical direction of Mr. Carl Gilchriest of the Jet Propulsion Laboratory (JPL). A six volume final report was written during the interval 12/78 and 6/79\*. Reproduction copies can be obtained through JPL.

During the "INTERPHASE" time interval between the end of PHASE I and the beginning of this PHASE II contract, the General Electric Co. continued to make model modifications and apparatus measurements. This work resulted in the model and implementation extensions shown on the following Figure C-1. The program listings contained in Volume 4 of this final report include all of these associated updates.

\*Section G of this volume contains a listing of sections of these PHASE I reports which are no longer applicable due to extensions and modifications made during this PHASE II work.

Extensions to Model and Implementation Made by  
The General Electric Company During the  
"Interphase" Between PHASE I and  
PHASE II

Figure C-1

3:2, 2:1 Transition Logic

Open Delta Transformer Connection Logic

More Compact and Better Organized Conversational Input for Analysis Programs.

Perturbation Logic Development Completed, Implemented and Arithmetically Validated.

Binary Tree Consistency Checking with Non Stop Diagnostics.

Line Type Consistency Checking with Non Stop Diagnostics.

More Efficient DPU File Directory Procedures

Absolute Frequency Available in Analysis Programs

Greatly Reduced Record Size in DPU and NT Files.

Network Reversing Program

Limit and Logical Input Error Detection Added to FEEDPUSj

Limit and Logical Input Error Detection Added to DISEM7Sj

Improvements in Program FEEDPUSj Operating Procedures

Improvements in Program FEEDPUSj to Greatly Reduce Disk Space for DPU Files.

New Program to Automatically Reformat DNWKINij Network Files

New Program to Compute Total Number of Transformers by Type in Network Files.

New Program to Automatically Generate Generic Three Phase Test Networks.

Two New Programs to Perform Reduction of Parallel Neutrals.

New Program to Extract a "Sub Network" Portion Out of a Network File.

New Program to Compute Three Phase Admittance Associated with Trapped Capacitor Bank (Neutral Trapping).

New Program to Simplify Generation of Three Phase Data Base Files.

#### D. PHASE II WORK STATEMENT

Following is a PHASE II Work Statement which has been edited to reflect certain small augmentations made since the contract award. This edited version has been included for reference to supplement Section I of this Volume 1, and also the more detailed tasks reported comprising Volume 2 of this final report. As such, only these portions of the Work Statement affecting the major work activities has been included.

The work of these tasks was performed under a program sharing arrangement between the Jet Propulsion Laboratory and the General Electric Company/Niagara Mohawk Power Corporation, in the following fashion:

##### Task (1) Verification

Entirely supported by the General Electric Company (GE) and Niagara Mohawk Power Corporation (NMPC). The principal contributors are listed in Section E of this report, but also include at times up to three technicians. All direct and indirect computing services and equipment (instrumentation, vans, etc.) were provided by GE. NMPC provided access to their distribution system (Groons Road Substation and its feeders), line crews (frequently 2) and "bucket trucks" to install various equipment and gain electrical access to the feeders, including the isolation of a long underground get-away cable for measurement.

##### Task (2) Perturbation

Originally this task was to have been supported by the contract. However, as a consequence of events, primarily the long INTERPHASE (see section C) and the manner in which measurements were made (both outbound

and inbound during the same field experiment), this task received considerable GE support. As a result, it is felt that the perturbation logic was developed to a higher state\*, more complete documentation was prepared, and more extensive validation accomplished than otherwise might have occurred under the original plans.

#### Task (3) Parameter Sensitivity

Most of labor cost associated with this task was supported by contract. However, the labor of a junior engineer was contributed by GE, and as well, the computing costs. It is again felt that this combined work resulted in a much more extensive investigation than would otherwise have been possible.

#### Task (4) Transformer Modeling

This task was almost entirely supported by contract. The exceptions were the computational costs and the contribution of NMPC in providing distribution transformers for measurement. Also included in the final task report are the supporting results of various measurements made as part of other GE internal activities.

#### Task (5) Investigation of Line Compensation

This task was also almost entirely supported by contract. The exceptions were the computational investigations reported in parts of Task (1) activities associated with simple terminations.

#### SUMMARY

In summary, it was the policy of the General Electric Company to provide, on a reasonable basis, the extra support that would gain a large

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\*Task (2) revisions were made to utilize cumulated voltage transfer matrices and reciprocity to vastly improve efficiency and make its use for distributed source analysis a feasible future development.

increment in "benefit/cost ratio" in terms of a more efficient computational procedure, better understanding, and better documentation. Also, it was the policy of the General Electric Company to fully disclose and incorporate in the documented software all the improvements that were developed during the INTERPHASE interval, so that the software documentation is current up to the "press time" associated with this report.



SCHEDULE

ARTICLE 1. STATEMENT OF WORK

- (a) The contractor shall, as a continuation of work begun under DOE Contract EF-77-C-01-2100, perform a Phase II Study of "RF Modelling of the Distribution System as a Communication Channel" which will consist of the following:
  - (1) Continue experimental verification of the analytic model by performing measurements on the target network as outlined in the Phase I effort with the following effect:
    - (A) Select a more highly loaded feeder where loads more closely approach the characteristic impedance of the feeder than the "ideal network", where verification measurements were previously made. This can be a combination of higher density housing and larger individual loads such as shopping centers.
    - (B) Select a longer feeder than the ideal network previously used that has a greater variety of installed hardware (power factor correction capacitors as an example) and that may have a greater number of voltage nodes in the frequency range less than 10 kHz.
    - (C) Select a feeder that has transitions between overhead construction and underground construction. Verification should demonstrate signals going from overhead to underground and from underground to overhead. These verifications may be selected from outbound or inbound signals.
    - (D) Select a feeder-secondary combination and verify that the model is capable of predicting signal levels at the "meter terminals" of the secondary. A two-step process of calculations consisting of feeder calculations and Distribution Transformer-secondary network calculations is acceptable.
    - (E) Extend the frequency range of verification to satisfy the objective of Phase I.
  - (2) Continue the "Perturbation Analysis" begun in the Phase I effort and:

- (A) Apply it to the calculation of inbound signals for the networks selected for (a)(1)(A), (B), (C), and (D) above.
  - (B) Perform verification measurements based on the calculations of (a)(2)(A) to demonstrate the usefulness of the "Perturbation Analysis" to predict signal levels from the "meter terminals" to the substation or other appropriate test point.
- (3) Perform a "Parameter Sensitivity Study" by exercising the computer programs developed in the Phase I effort with variations of the parameters to:
- (A) Determine the significance of the various parameters.
  - (B) Determine if the "set up" time for the computer inputs can be significantly reduced.
- (4) Perform studies of "transformer modelling" to obtain discrete parameter models from the measured data on transformers of Phase I to attempt to correct the "physically realizability" problems encountered in Phase I. This effort is to be applied to both Distribution Transformers and Ratio Bank Transformers. If this modelling is successful, incorporate it into the computer programs developed in Phase I.
- (5) Investigate further techniques to alter or work around the performance of "trouble spots" such as the termination used to correct high standing wave ratios encountered in Phase I.
- (6) Prepare and distribute 40 copies of Phase I Final Report required by DOE Contract EC-77-C-01-2100 in accordance with a distribution list to be furnished by JPL.
- (7) Provide Phase I computer programs and files to the GE time share computer for JPL to exercise by telephone.
- (8) The contractor shall prepare and deliver to JPL the following documentation in the numbers and copies specified as follows:
- (A) One (1) copy of a Monthly Technical Status Report.
  - (B) Five (5) copies of a Monthly Contractor's Financial Management Report, NASA Form 533M, March 1973, prepared in accordance with the instructions contained on the reverse side thereof.
  - (C) Ten (10) copies of a Preliminary draft of the Final Report.

Contract No. 955647

- (D) One (1) reproducible and forty (40) copies of the final report incorporating JPL comments.

## E. ACKNOWLEDGEMENTS

The purpose of this section is to identify and acknowledge the contributions of the various organizations and individuals who have been involved in this work.

### Jet Propulsion Laboratory (JPL)

Carl E. Gilchrist, JPL Technical Manager

J. H. McConkey, JPL Contract Negotiator

### Niagara Mohawk Power Corporation (NMPC)

Roosevelt Fernandes

Fred Rushden

### Utility Industry Advisors:

J. Blase, Philadelphia Electric

W. Blair, Electric Power Research Institute

E. W. Downey, The Cleveland Electric Illumination Co.

J. Kortochinski, Ontario Hydro

### General Electric Company - Corporate Research & Development (CRD)

C. A. Stutt      Manager

R. C. Rustay      Principal Investigator/Transformer  
Modelling/Parameter Sensitivity  
Software Development and Maintenance/  
Model Development.

General Electric Company -- Corporate Research & Development  
(CRD)

R. W. Rankin	Transformer Modeling/Field Verification Measurements.
R. Wooding	Verification Modeling and Calculations/ Cable Modeling/Software Development/ Trouble Spot Diagnosis and Compensation.
R. Wentz	Parameter Sensitivity/Software Development
W. C. Hughes	Field Verification Measurements

Union College

J. T. Gajjar	Consultant/Trouble Spot Diagnosis and Compensation/Software Development and Maintenance/Transformer Modeling.
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#### F. ORGANIZATION OF PHASE II FINAL REPORT VOLUMES

The final report of the PHASE II work is contained in the following volumes:

Volume 1	Summary Report
Volume 2	Task Reports
Volume 3	Appendices (See Fig. F-1 for Table of Contents)
Volume 4	Software Source Program and Illustrative ASCII Database Listings

For convenience, a Table of Contents for Volume 3 is attached as Figure F-1.

## VOLUME 3 APPENDICES

### Table of Contents

1. Tutorial Review of Exact "Perturbation" Theory as Implemented in DIFNAP Software Program NTWKANSj - R. C. Rustay.
2. Using Reciprocity to Compute Reverse Direction Voltage Transfer Ratio Matrices - R. C. Rustay
3. Y Parameter Analysis of Symmetric Distribution Transformer with Balanced Loading and Brief Discussion of RLC Lumped Parameter Model - R. C. Rustay
4. Program for Computing and Plotting RLC Transformer Model Predicted Responses - R. C. Rustay and R. C. Wentz
5. Matrix Based Generalized Neutral Reduction Program - R. C. Rustay
6. Main Program NETGENS1 for Generating Generic Networks - R. C. Rustay
7. Main Program SUBNETS1 to Extract Subnetworks - R. C. Rustay
8. Network References - R. C. Wentz

Figure F-1

## G. COMMENTS ON PHASE I FINAL REPORTS

Since the edition date of the PHASE I final reports, many improvements and modifications have been made in the model and software implementation, and as a result, various portions of the PHASE I reports are either not current or are obsolete, to be replaced by updated material. This section lists such portions, with comments as appropriate. PHASE I final report sections not listed below can be assumed still applicable.

The following codes will denote

N/A No Longer Applicable

M Requires Modification

<u>Section</u>	<u>Code</u>	<u>Title</u>
<u>PHASE I - Volume 1 - Summary</u>		
O	M	<u>Tutorial Overview to Modeling Feeder Network for PLC Propagation</u> See Section M of this PHASE II volume
P	M	<u>Status of the Model and Computer Program</u> See Section K of this PHASE II volume
<u>PHASE I - Volume 2 - Program and System Reference Manual</u>		
SD	M	<u>The DIFNAP System</u> Delete references to files: DATRANij DASECDij DARBTRij



<u>Section</u>	<u>Code</u>	<u>Title</u>
MP	M	<u>Main Program Description</u>
		<p>Delete references to above files.</p> <p>Listings of NTKERS1 and NTKANS1 are obsolete and should be replaced by counterparts in Phase II, Volume 4.</p> <p>Refer to following Figure G-1 for revised LTYP code convention.</p>
DB	M	<u>ASCII Data and Random Binary Database File Description</u>
		<p>Delete any reference to files:</p> <p>AFRBTRij     DARBTRij</p> <p>Replace by ASCII file RBTRDATA explained in Phase II Volume &amp; History for NTKERS4.</p> <p>AFTRANij     DATRANij</p> <p>Replace by user named file - see subroutine TRANADS4 in Volume 4.</p> <p>AFSECDij     DASECDij</p> <p>Analytic Transformer Model not yet implemented.</p> <p>Figure DB1-1 - replace line number 1128 with line number 1140.</p> <p>Page DB2-1, add FREQ (in kHz) to line 1010.</p> <p>Page DB3-1, delete references and data columns corresponding to LTYO and ICCD.</p> <p>Page DB3-5, Figure DB303, replace by Figure G-1 of this volume.</p> <p>Page DB13-1, structure of the NT_____ file has been revised. See listings of NTKERS4 and NTKANS4.</p>
DP	M	<u>Description of Main Programs for Generating .....</u>
		<p>Only the discussions concerning SFPRYLS1 are applicable; source listing in Volume 4 for SFPRYLS2 is current version. Similarly for FEEDPUS5.</p>

<u>Section</u>	<u>Code</u>	<u>Title</u>
S0	M	<u>Subroutine Program/Library Description .....</u>  PHASE 4, Volume 4, contains complete set of current versions of all sub programs. See annotation/comments imbedded in each source for further detail.
MI	N/A	<u>Miscellaneous Programs</u>  No longer applicable.

PHASE I - Volume 4 - User Handbook

SF	M	<u>Surveying Feeder Network</u>  Page SF-1, replace "three .... single phase branching" with "3:2, 3:1, 2:1 Transition".
AD	M	<u>Augmenting/Building Data Base Files</u>  Page AD-1, Delete all references to DARBTRij, DATRANij, DASECDij files.
OD	M	<u>Operation of the DIFNAP System Procedure</u>  Delete all references to above files.  Beginning page OD-3 and thereafter, use only as general guide: conversational interaction structure has been modified.

PHASE I - Volume 5 - Statistical Analysis on the Driving Point Admittance

This approach has not been further pursued in this PHASE II.

## H. DESCRIPTION OF THE NIAGARA MOHAWK POWER CORPORATION FIELD TEST AREA

This section briefly describes the Niagara Mohawk Power Corp. (NMPC) feeder #34556 originating out of the Grooms Road Substation located in Clifton Park, N.Y. (near the tri cities area of Albany, Troy and Schenectady). It is on this feeder that most of the verification measurements have been made for this PHASE II (and PHASE I).

This feeder, #34556, is a radial distribution circuit with a main trunk-circuit of about 10 miles and operates at 13.2 kv line-to-line (WYE) except for two single phase sections operating at 4.8 kv line-to-line and supplied by 7.62-4.8 kv ratio transformers. Distribution transformers on these two 4.8 kv single phase branches are connected phase to phase. Elsewhere they are connected line to neutral.

Additional features found on this feeder are:

1. Power factor correction capacitors
2. Direct buried underground cables
3. Ratio transformers (two)
4. "Densely" loaded residential areas
5. Three phase commercial and light industrial loads
6. Long single phase branches
7. Overhead-underground transitions
8. Considerable variety of overhead conductor geometry and conductor sizes.

A sketch of the feeder #34556 is shown on Figure H-1. Note that much of the loading is served by a relatively long "trunk". The verification sub tasks summaries to follow and the detailed reports in Volume II will frequently refer to this circuit.

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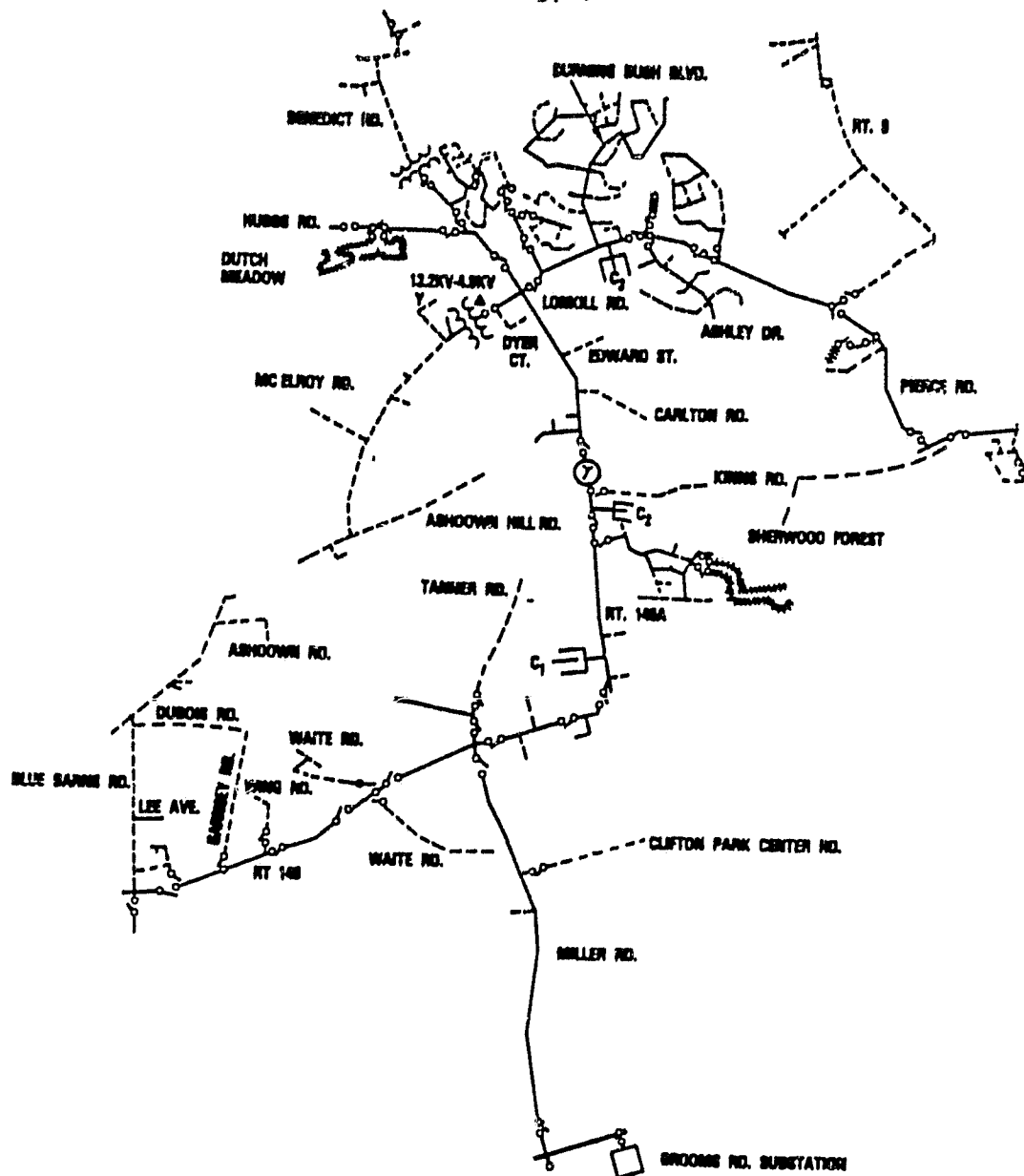


Figure H-1. Sketch of NMPC Feeder #34556

## I. SUMMARY OF TASK ACTIVITIES

In this Section, a brief summary will be given of the work and conclusions associated with each of the tasks specified in Section D of this volume. The following Figure I-1 is a quick reference guide.

<u>TASK</u>	<u>TITLE</u>
(1)(A)	Densely Loaded Feeder Sections
(1)(B)	Full Size Distribution Feeder
(1)(C)	Overhead-Underground Transitions
(1)(D)	Meter Terminals on Secondary
(1)(E)	Extended Frequency Range
(2)(-)	Continue "Perturbation Analysis"
(2)(A)	Perturbation Calculation of Inbound Propagation
(2)(B)	Inbound Path Propagation Measurements
(3)(A)	Parameter Sensitivity-Significance of Parameters
(3)(B)	Parameter Sensitivity-"Set-up" Time Reduction
(4)	Transformer Modelling
(5)	Line Compensation and Termination Techniques

Figure I-1

List of Task Titles

### Task (1)(A) Densely Loaded Feeder Sections

The work of this subtask was concerned with the verification of the model on a densely loaded network. A part of the 34556 feeder which originates from Niagara Mohawk Power Company's Grooms Rd. Substation in Clifton Park, N.Y. was chosen for this purpose. The nominal operating voltage of this feeder is 13.2 kv line to line. Figure 1 shows the general location of the densely loaded section in relation to the total feeder. Figure 2 is part of an operating map provided by the utility showing the densely loaded section in more detail. This feeder section was selected for study because of the relatively large number of distribution transformers per unit length of circuit.

A carrier voltage was placed on the feeder phase conductors at a capacitor bank location, shown at Point 1, Figure 2. Coupling was accomplished by connecting the transmitter to the common point of the capacitors and an inductor which completed the circuit to neutral. The inductor was originally placed in the capacitor bank ground lead in order to prevent the bank from providing a large current sink to the carrier signals. The transmitter voltage was monitored at this same point.

A coupling network with appropriate carrier frequency voltage measurement equipment was connected near the end of the densely loaded section. This measurement apparatus was located at Point 2, Figure 2, and was capable of measuring each phase voltage.

A power factor correction capacitor bank was located at another terminal point of the densely loaded section. This bank was located at Point 3, Figure 2. An inductor was placed in the ground lead of

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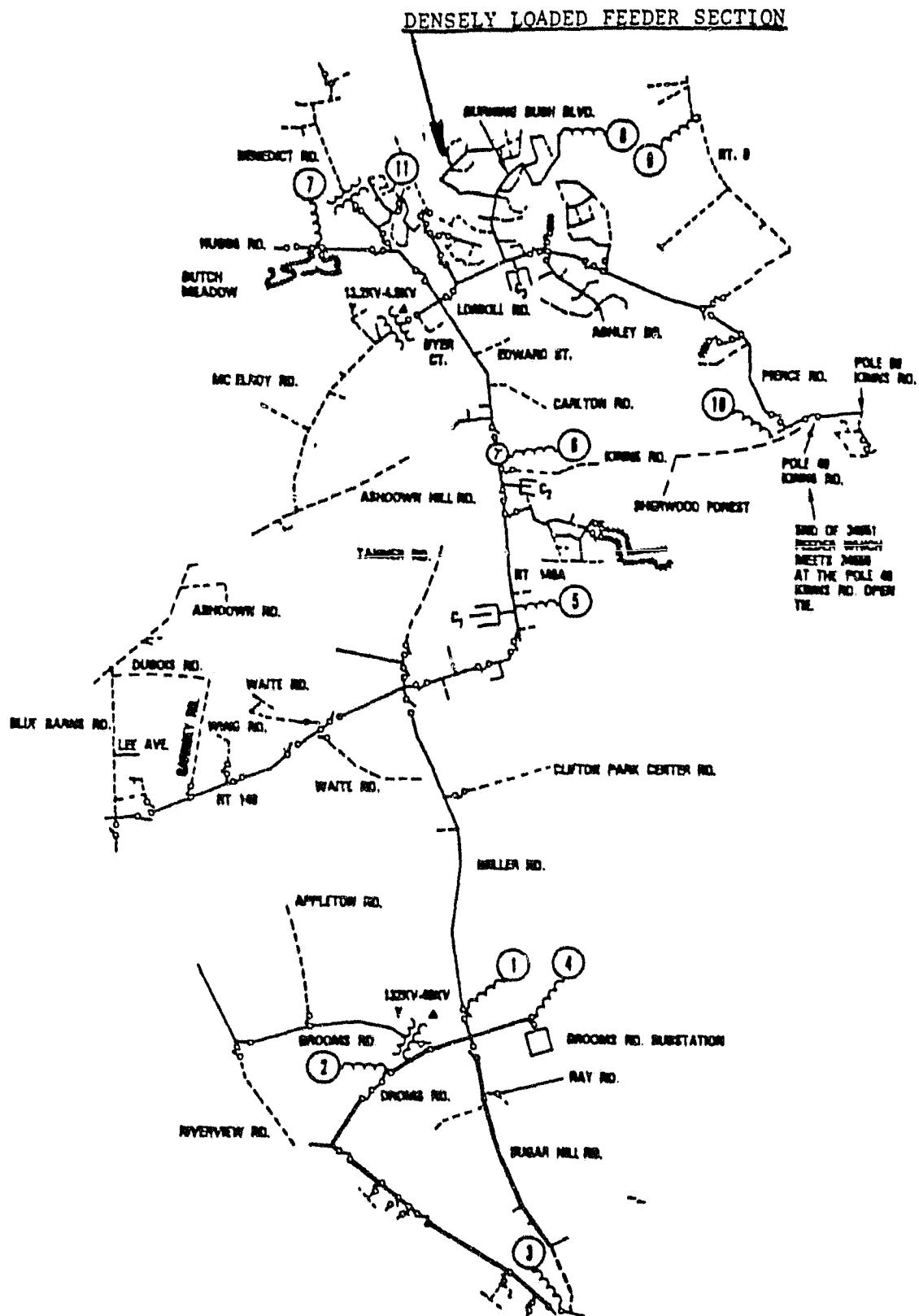


Figure 1



2-11-1

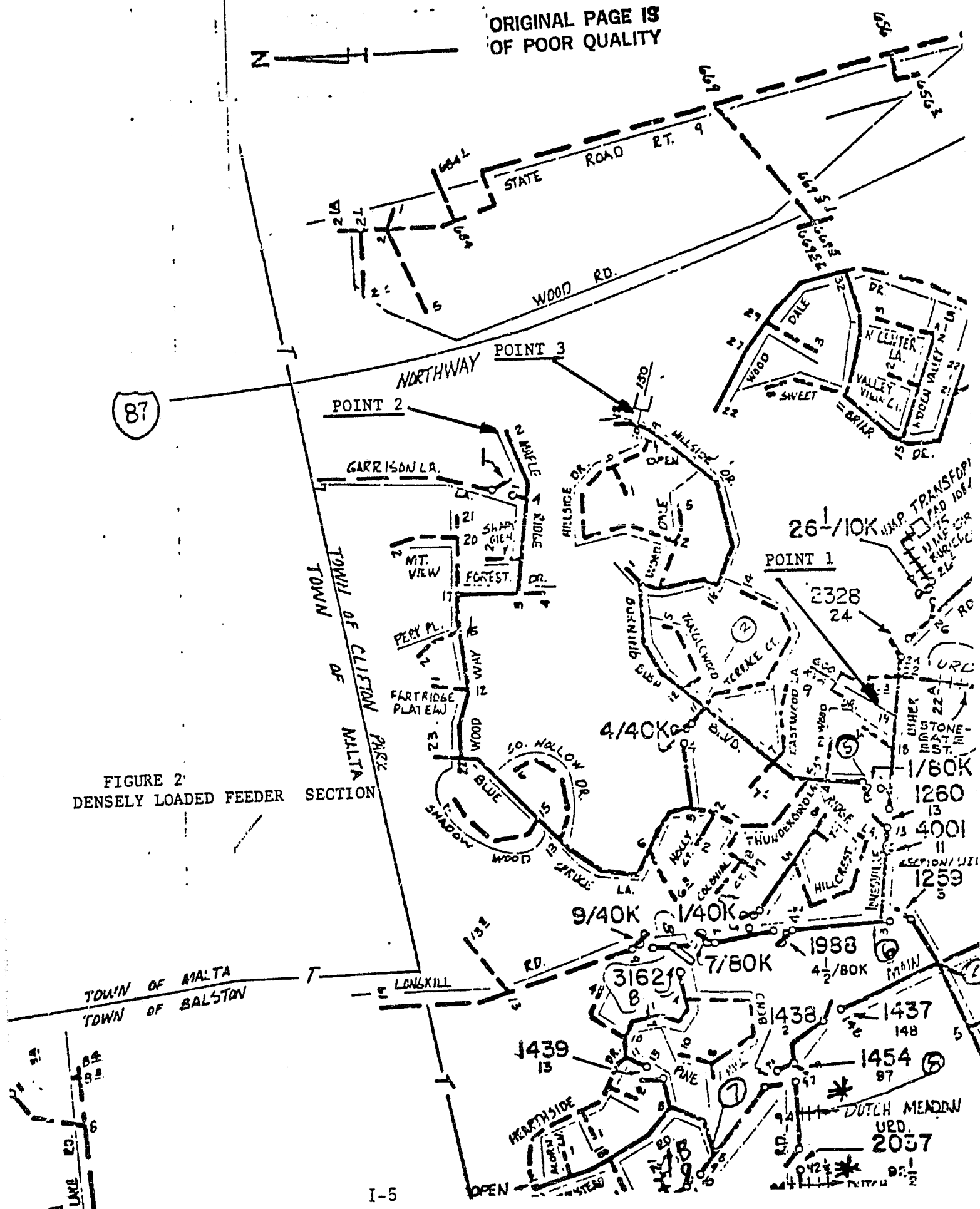


FIGURE 2  
DENSELY LOADED FEEDER SECTION

I-5

this bank also for the reason mentioned above. The carrier frequency voltage across this inductor was recorded during the measurements.

The end result of the field measurements were voltage transfer ratios. Individual phase voltages at the transmission point were calculated by use of the measured transmit voltage at Point 1. By assuming the admittance of the power factor correction capacitors was much larger than the admittances seen looking out onto the feeder network at the capacitor bank location, the phase voltages at the capacitor bank are nearly equal to the voltage at the transmission point. Knowledge of these phase voltages at the transmission point provides a means to calculate individual voltage transfer ratios for each phase between Point 1 and Point 2 on Figure 2. Also, since the inductor voltage (a vector sum representative of the phase voltages at that point) was measured at the capacitor bank at Point 3, voltage transfer ratios between Point 1 and Point 3 were calculated from the measurements.

The inductor voltage calculations in the simulation were performed off-line. Given a knowledge of the admittance matrix of the capacitor-inductor network at Point 3, the capacitor current vector  $[I = YE]$  could be calculated by using the phase voltages provided by the program at that point. The vector sum of these currents was then used to calculate the carrier frequency voltage across the inductor. The inductor voltage is centrally about 10 db lower than the vector sum of the phase voltages.

The model simulations show agreement of sufficient accuracy with the measured data for communication system engineering purposes. The model results are influenced somewhat by the loading level of the distribution transformers. The power factor of the load on the

distribution transformer secondaries was assumed to be .8 lagging. It should also be kept in mind the model assumed a time invariant network with respect to loading, while during the field test there probably was some variation in the feeder loading.

### Task (1)(B) Full Size Distribution Feeder

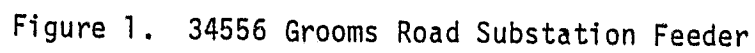
The work of this subtask is concerned with verification of the model on a full size distribution feeder having a variety of installed hardware and topology.

Feeder 34556 of the Niagara Mohawk Grooms Road Substation in Clifton Park, N.Y. was selected for this purpose. The feeder operating voltage is 13.2 kv line-to-line with single phase sections where the operating voltage is reduced to 4.8 kv line-to-line. These sections are shown in Figure 1. Simulations of these measurements were performed using the DIFNAP system programs in order to verify their utility in predicting distribution line carrier propagation as an aid to communication system engineering.

Feeder 34556 is a radial distribution circuit. The total length of the main trunk circuit is about 10 miles. The following common distribution system features are found on 34556.

- 1) Power factor correction capacitors
- 2) Direct buried underground cables
- 3) Ratio bank transformers (13.2 kv-4.8 kv)
- 4) Long single phase branches
- 5) "Densely" loaded residential areas
- 6) 3Ø commercial & light industrial loads
- 7) Several different overhead conductor geometries and conductor sizes.

The points labeled 1, 3 & 4 on Figure 1 denote the location of 3Ø capacitor banks. An inductor was placed in the ground lead of the capacitor banks in order to prevent the capacitors from providing a large current sink to the carrier signals. During the measurements,



the carrier voltage across the inductor was monitored and recorded to give an indication of the vector sum of the phase voltages. Sufficient precautions were taken to prevent 60 Hz voltages from affecting the carrier voltage measurements.

Individual phase voltages were monitored at point (2), Figure 1. At this point, access was gained to the individual overhead phase conductors. Within a few hundred feet of this pole is a cable riser providing service for the Country Knolls West residential area which is served by direct buried underground cable. Extensive measurements and DIFNAP simulations on this cable network were reviewed in a previous report. The coupling network employed at Carlton Rd. (point 2, Figure 1) is shown in Figure 3.

During the field measurement, three distinct conditions existed on the feeder which were treated by simulation. These conditions were:

Condition 1. No coupling network connected at Carlton Rd. Inductor voltages were monitored at Points (1) and (3) shown on Figure 1. Transmit voltages were monitored on Phase A at the substation as shown in Figure 4. Phase voltages were assumed equal at the substation for modeling purposes.

Condition 2. Coupling network connected at Carlton Rd., but with tuning inductors disconnected. Individual phase voltages were monitored at Carlton Rd. Inductor and transmit voltages monitored as in Condition 1.

Condition 3. Coupling network connected with tuning inductors in place at Carlton Rd. The same quantities mentioned in Condition 2 were again recorded.

Simulations were performed at the following frequencies:

5010 Hz  
6990 Hz  
8130 Hz  
9510 Hz

Corresponding to measurements performed on the feeder.

The simulations performed on the 34556 distribution feeder and subsequent comparisons to measured results were subject to several assumptions, these being:

- 1) The network configuration was specified accurately by utility personnel and on system maps.
- 2) Conductor lengths specified on utility map were accurate for engineering purposes.
- 3) The assumption that each transformer was loaded to 20% of full kva capacitor with a .8 power factor lagging load was a valid representation for the feeder loading.

Under this assumption, the total connected load kva employed in the model was 3200 kva, if the load factor mentioned above was assumed. The measurements were performed during off-peak loading hours for the most part under moderate climatic conditions with respect to heating and cooling loads.

- 4) The coupling and tuning network components were known with sufficient accuracy for model purposes, and loss components present in these circuit elements were negligible at the frequency of interest.

- 5) Errors in field voltage measurements and data reduction were minor.

In general, the predictions and measurements were within 6 dbv of each other. This should be sufficient accuracy for communication system engineering given an accurate knowledge of feeder noise characteristics. Since the voltage transfer ratio of the feeder is sensitive to loading level, it would also be advisable for engineering purposes, to study the feeder response parametrically as a function of loading level in order to bracket system performance limits.



### Task (1)(C) Overhead-Underground Transitions

The work of this subtask was concerned with measurements on three distinct physical situations, and detailed descriptions and results are contained in the following internal reports which are included as part of Volume 2:

- A. Analytical Verification of G.R.S.S. Underground Cable Verification.
- B. Underground Cable Tree Network Measurement Verifications
- C. Model Verification of Field Measurement Performed on Carlton Rd. O.H.-U.G. Network

all written by R. Wooding. The physical situation in B. involved an area called Country Knolls South, served by Niagara Mohawk Power Corp. (NMPC) feeder #34551, and in general, consists of a large trunk cable with a number of single phase branches implemented with smaller conductor cable. The main trunk cable is about 1600 meters long and is composed of 500 KCMIL concentric neutral cable. The single phase branch circuits are composed of #2 A.W.G. concentric neutral cable. The physical situation in C. involved a lateral off NMPC feeder #34556 and consisted, in approximate terms, 650 meters of three phase open wire overhead feeding a large underground trunk cable of 500 meters length. Several single phase feeder cables branch from this trunk and have a total accumulated length of approximately 600 meters. The trunk cable and feeder cables are the same as above for B.

Chronologically, it was first attempted to verify (predict and compare with measurements) case B. using the BPA EMT cable parameters

program. However, the generic cable parameter models contained therein were not well suited to the physical construction of the actual cables which were "complicated" by a helically wound "skid" wire outer sheath, two internal concentric semi conductor sheaths for electric field control and a separate bare copper ground wire also buried in the trunk. Using this software required considerable approximations and also for the reason later determined to be an incorrect value for the dielectric constant, the calculated prediction of propagations did not agree very well with measurements. Looking at the data suggested that calculated velocity of propagation in the cable was not proper.

After significant effort to reach the above conclusion, it was decided to seek out a location where measurements could be made on an "ideal" unbranched U.G. cable. With the cooperation and very significant effort of NMPC, an U.G. 750,000 CMIL, unbranched trunk cable of length 1.98 miles, was isolated and made available for our measurements. The details and results are reported in A. above. In addition, a new program UGZYGES1 was written by R. Wooding to more appropriately compute the cable parameters.

Both transient (periodic pulse) and steady state CW (2 to 100 kHz) excitations were applied for a variety of terminations and connections. One immediate result of these measurements was to determine (from both the transient pulse time delay and the CW phase roll measurements) that the cable length was slightly different (approximately 5%) than indicated by the maps. Using the BPA EMT cable parameters program with proper dielectric constant (for Kerite) still resulted in unsatisfactory verification due to the lack therein of a generic cable model tailored to the actual construction involved. The new cable parameter

program did lead to very good verification results for case A.

Some significant conclusions reached from case A were:

- 1) As expected, the electro magnetic field coupling between the three phases, although quantitatively predicted, is practically so small as to be negligible, i.e., the three phase cable behaves essentially like 3 electrically isolated single phase cables.
- 2) The characteristic impedance was approximately  $15.5\Omega$  and speed of propagation about .35 free space.
- 3) The main diagonal elements of the measured and predicted driving point admittance (DPA) matrix agreed very well with frequency (after the map determined length was modified to the length determined by measurement).
- 4) Off diagonal elements of the DPA did not agree well but for understandable and negligible importance. As mentioned above, the EM coupling between phases is believed to be small, so that any external unmodeled conductive coupling, although small\*, could effect the measured off diagonal elements. In any event, it is believed that because the off diagonal elements are small in either case (measured and computed), they are quickly "lost" in any applications due to other phase-to-phase effects.
- 5) During these prediction calculations, some insight was obtained regarding the influence of factors such as:
  - a) earth resistivity
  - b) main conductor and neutral wire temperature
  - c) physical spacing of conductors in trunk
  - d) exact dielectric constant of insulation system
  - e) actual cable length.

\*In fact, measurements with open receiving end termination indicated this.

The apriori cable length information is apt to be the most critical since, to a first approximation, it is directly related to frequency response effects.

Having now, in time chronology, obtained what is believed to be a credible cable parameter model, work on Items B. and C. were redone.

The verification work for situation B (Underground Tree Network) was entirely devoted to comparing measured and predicted DPA matrices at discrete frequencies between 5 and 25 kHz. Assuming all distribution transformers (DT) resistively loaded at 40% of their full load rating, what is considered to be very good results (for PLC design) were obtained for the main diagonal elements, say like 6 db and 15 degree errors in magnitude and phase, respectively. It is, of course, realized that these main diagonal elements are significantly effected by DT loading (phase to neutral), cable length and to lesser extent, earth resistivity and cable temperature assumptions. Again, as in situation A, the off diagonal terms in both cases (measurement and predicted) were much smaller (on the order of 30 db) than the diagonal elements, and therefore of negligible importance.

In situation C (Carlton Road O.H.-U.G. Network) the branch DPA matrix was measured as before and also the magnitude of the voltage transfer to several DT secondaries were measured. Also, these same quantities were measured vs. frequency with a reactive load placed on the end of the trunk cable to partially compensate the line. Again, the verification results were very good (subject to assumption of DT loading level) and some of the significant conclusions were:

- 1) The relatively short overhead section provided substantial amount of interphase (EM) coupling.

- 2) The DPA comparison showed agreement including the off diagonal elements which now are not small compared to main diagonal elements due to the OH interphase EM coupling.
- 3) The predictions and measurement of DT secondary voltage showed good agreement especially considering the fact that at this time no attempt was made to account for the effect of frequency and load on the voltage transfer across the DT. It is believed that this agreement helps substantiate the models ability to predict down to the DT secondary terminals.

As before, apriori values for loading and line length are significant.

As an overall conclusion reached as a result of these three

Task (1)(C) activities is that:

- a) Apriori uncertainties in parameters, especially line lengths may typically limit the frequency range of modelling to, say, 25 kHz. Given more exact parameters, and the effects of apparatus loading at higher frequencies, no frequency limitation is as yet known.
- b) The effects of unknown loads at any instant of time does not represent a defect in the modelling, i.e., such an effect actually exists in "real life". Therefore, it is suggested that such variable loading effects be investigated parametrically via the model for various loadings considered typical.

### Task (1)(D) Meter Terminals on Secondary

The purpose of this subtask was to verify the models ability to predict voltages at the "meter terminals" on the secondary service of distribution transformers. Inasmuch as it was not planned as part of this PHASE II effort to have a distribution transformer analytic model implemented, the equivalent prediction is presently performed by a "two step" process. The first step is to predict propagation on the feeder with distribution transformers (DT) represented by a phasor admittance load connected to the proper phase and representing the DT primary driving point admittance associated with the specified DT and connected secondary load. Then having the predicted feeder phase voltages, an off-line calculation or response curve look up could be used to predict the DT secondary terminal voltage. The voltage propagation down to the meter terminals could also be done off-line using electrically short (primarily a lumped series impedance) secondary circuit representation.

Originally it was hoped to find a DT on NMPC feeder 34556 which had a single customer at the end of a long secondary service. To verify with a "multi drop" secondary would have required simultaneous measurement of each customer load-current and voltage which was not considered feasible. However, no long single customer service was found. Therefore, no uniquely applicable test and verification was conducted.

However, several related activities and characteristics have some positive bearing on this objective. First, as part of TASK 1C, propagations were made from a location on the feeder (removed from the DT

location) to the secondary terminals of various DT's, and the results were supportive. Secondly, as part of TASK 4 DT modeling extensive response measurements were made that show, for the lower frequency range (say less than 25 kHz) the primary to secondary transfer is primarily the turns ratio effect with a few DB accounting for reactance drop caused by secondary load. Finally, any voltage drops on the secondary circuit would depend on an estimate for the simultaneous loads for each customer. Since the secondary circuits are electrically short, the computation, given the loads, presents no conceptual problem.

It is believed, therefore, that compared to predicting propagation on the feeder, analysis of the DT primary to secondary (terminals) transfer and prediction on the secondary terminals present no conceptual difficulty.

TASK (1)(E)  
Extended Frequency Range\*

The objective of this subtask was to extend the frequency range of verification to satisfy the objective of PHASE I. Because of technical considerations mentioned in 1) and 2) below, it was deemed higher priority to verify first the models capability at the lower frequencies. Hence, the other tasks associated with verifying the model were given scheduling priority. For the reasons cited below, the work called for by this task was not accomplished.

1) Uncertainties in Specifying Line Lengths

As work progressed to the point of verifying the model at lower frequencies, it was realized that apriori estimates (based on utility records) of line lengths are not always reliable. The effect of uncertainties in the knowledge of actual line lengths is conceptually evident for unloaded transmission lines, i.e., line length  $z$  analytically always appears in the factor  $\frac{fz}{v}$  where  $v$  is the speed of propagation, so that at higher frequencies, an error in assigned length corresponds to a higher fraction of a wavelength. Note also that a slower speed of propagation also further aggravates the effect of line length errors. This trend still exists in the presence of line loading. Experiences during verification, see Task 1-C "GRSS U.G. Getaway" and "Country Knolls South U.G. Network" indicate that 5% errors in line length estimates are not unreasonable. Based on our experience (somewhat confounded by other higher frequency effects) we judge that 50-100 kHz may be a reasonable upper limit.

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\*This material is verbatim from Volume 1



## 2) Transformer Response

As the transformer modelling and measurements progressed, it appeared more and more promising that with a simple extension (to the 60 Hz R-L-M two winding transformer model, a lumped parameter model could be used to predict transformer response up to 25-50 kHz and which was not too sensitive to variations in construction, i.e., with the simple extension the similarity of 60 Hz performance could be extended to 25-50 kHz. (Characteristics do vary with KVA). Beyond this frequency range, variations in response at PLC due to differences in manufacturing construction may become important. If this is true, then either a much more detailed inventory of transformer characteristics and identification of installed transformers is required, or additional modeling errors accepted.

## 3) Resource and Time Limitations

During the process of verifying the model, several contingencies were encountered. One involving line length uncertainties was mentioned above. The most significant contingency involved verification with circuits involving underground cables. Identifying the source of the problem, arranging for appropriate tests (see Volume II, Task (1)(C), writing a new cable parameter program involved considerable effort and delay. Another contingency involved making admittance measurements of the Grooms Road Substation. Special measurement equipment had to be designed and built and special facilities installed by Niagara Mohawk Power.

As a result, resources (and time) were not available to proceed with higher frequencies.

4) Vendor Trends to Lower Frequencies

Supporting the above stated priority is what appeared to be a trend by virtually all parties to gravitate to the lower frequencies for distribution feeder communication.

### Task (2)(-) Continue "Perturbation Analysis"

This subtask 2(-) is concerned with the continued development of "exact perturbation" analysis to include reverse path propagation from any remote point on feeder back to the original source or to any other point. Also included in this subtask is the coding, implementation and arithmetic validation of the coding.

Because this capability was needed for an unrelated application during the INTERPHASE interval before commencement of PHASE II, this work was actually completed using General Electric resources.

A tutorial review of the underlying theory is contained in PHASE II, Volume 3, Appendix 1 with relevant material also contained in Appendix 2.

The coding was arithmetically validated by comparing the results for reverse path propagation using the exact perturbation theory with that obtained by "reversing the network" to make the new source point a new root node and the original root section just another section. This network reversing procedure was accomplished by a software program NETREVS1, also written and tested during the INTERPHASE and whose listing is contained in PHASE II, Volume 4. The load perturbation logic was similarly validated by comparing perturbation predictions against those obtained by rerunning NTWKERSi and NTWKANSi with the revised load and sources.

Note that the perturbation reverse path logic/procedure allows a completely general matrix Norton's Source representation to be applied anywhere, not just (but including) an ideal current injection or an ideal voltage source (which can be created by using an ideal current source with values automatically determined by program).

The advantages claimed for this perturbation procedure are:

- 1) Economical and convenient computation of single load variation effects, such as faults, on propagation.
- 2) Economical and convenient computation of propagation from any new (completely general matrix-vector Norton's) source location to any other point in network, not necessarily, but including the original source.
- 3) Extendability to the computation of propagation to any point due to any number of "dispersed" sources throughout the network.

The perturbation procedure is implemented in NTWKANS4 in conversational/interactive fashion which is reasonably self prompting on execution.

The key items making the perturbation procedure possible and practical are:

- 1) The two phase network analysis, i.e., the descending admittance reduction performed by NTWKERSi and the ascending propagation and Norton's source parameters calculated by NTWKANSi.
- 2) Appropriately saving on a random binary file prior computed results for each section.

Task (2)(A) Perturbation Calculation of Inbound  
Propagation

This subtask was concerned with using the implemented perturbation technique to predict inbound/reverse propagation. What actually was done was to predict inbound propagation using both perturbation techniques and an alternate procedure involving a "network reversal" operation\* followed by a normal outbound prediction from the "new" source to, say, the substation. The purpose of using this alternate procedure was first to give an "exact" numerical check on the perturbation arithmetic implementation and also as a more convenient procedure for the general verification of the model. The result of this model verification is contained in Task (2)(B) report "Model Verification-Inbound Path Propagation". The arithmetic results using the perturbation and the reversed network procedures gave exactly (except for negligible differences due to numerical round-off considerations) the same results in all cases. Similar comparisons were made on other synthetic networks designed to test various topological considerations, and again the results were identical. As a result of these tests, it is believed that the implemented perturbation logic is validated.

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\*A main program "NETREVSI" was implemented during the INTERPHASE interval and which can automatically generate from a given network file a new network file having a specified remote node as a new source.

### Task (2)(B) Inbound Path Propagation Measurements

The work of this subtask involved inbound signal propagation measurements on a "typical" 13.2 kv distribution feeder and, in particular, the 34556 feeder on Niagara Mohawk's Grooms Road Substation in Clifton Park, N.Y. Inbound transmissions were coupled to the feeder via a capacitor bank located about 7.7 miles away from the substation. Inbound signals were measured at an intermediate point and at the substation.

It was not possible to readily measure individual phase voltages at the substation during the field measurements. The individual phase currents at the substation were readily available, though. Therefore, individual phase currents were used for model verification purposes at the substation.

Measurements of inbound signal propagation were made under three conditions at the intermediate point:

- 1) No coupling and measurement apparatus
- 2) Coupling and measurement equipment attached. No tuning inductors attached.
- 3) Coupling and measurement equipment attached. Tuning indicators attached.

Therefore, under condition (1), no voltage measurements were obtained at this intermediate point.

For conditions 2 and 3 where measurements at Carlton Road were available, the agreement with predictions was generally very good. The agreement for the substation phase currents was not as good, possibly for reasons to be mentioned below, but are still considered useful for design.

When making calculations of inbound signal propagation, it was necessary to find some representation for the admittance looking back into the substation itself. The substation admittance matrix was obtained by field measurements which were not performed at the same time the inbound propagation measurements were made. Since the 34556 feeder shares a common substation bus with other distribution feeders, the input admittance of the substation could be quite variable due to changing load levels on the other feeders sharing that bus. Also, the current transformers at the substation are subject to saturation effects because of the relatively large 60 Hz currents present at the substation and could contribute to discrepancies between measured and calculated carrier currents at the substation.

The results seem to support the view that uncertainties in the substation admittance and current measurements\* may be the cause of the larger divergence between prediction and measurements. It is observed that because the substation admittance will usually be high (relative to other system admittances) that it will highly correlate with the voltage/currents which will actually occur, and for the same reason, the predictions will be strongly sensitive to uncertainties in specifying its value. None the less, it is felt that useful predictions, say based on worst case assumptions, will be useful for design purposes, and in fact, reflect requirements placed on the design.

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\*Also involved in the separate measurement of the substation admittance.

### Task (3)(A) Parameter Sensitivity - Significance of Parameters

The purpose of this task was to investigate the sensitivity of such computed items as voltage propagation, driving point admittances (DPA), etc. to such items as variations in line construction, conductor temperature, earth conductivity, etc. These sensitivities would offer guidance to such (example) questions:

- a) Does the proximity effect of various miscellaneous conductors significantly effect the solution, or can they be neglected?
- b) How serious are errors in estimating conductor temperature, earth resistivity, line lengths?
- c) Is it necessary to distinguish between small dimensional changes in line configuration and/or conductor size?

It is expected that these sensitivities, for the reasons implied, will also possibly enable some time saving in the preparation of input files and data base files if these can be reduced in number and variety.

The various "independent" variable items considered are shown in Tabulation (3)(A)-1.

For those items affecting the transmission line parameters, their effect on the eigenvalue vector and the characteristic admittance matrix were examined by computing and comparing one at a time\* for the listed items, the resulting variations in the eigenvalues and the characteristic admittance against a "nominal" case. Where the "continuous"

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\*Some "two at a time" variations were also considered.



TABLE (3)(A)-1

Variations

- \*1. Phase conductor diameter.
- \*2. Neutral conductor diameter
- \*3. Phase conductor to phase conductor spacing
- \*4. Phase conductor to earth spacing
- \*5. Neutral conductor to earth spacing
- \*6. Miscellaneous conductors added
- \*7. Triplex neutral conductor
- \*8. Spacer cable configuration
- \*9. Diagonal load at the end of the line removed
- \*10. Admittance of each D.T. load doubled
- \*11. Diagonal load removed and D.T. load admittances doubled
- \*12. All D.T. loading neglected
- 13. Admittance of each D.T. load cut in half.
- 15. Phase conductor diameter and admittance of each D.T. load cut in half.
- 15. Neutral conductor diameter and admittance of each D.T. load cut in half.
- 16. Phase conductor to phase conductor spacing and admittance of each D.T. load cut in half.
- 17. Phase conductor to earth spacing and admittance of each D.T. load cut in half.
- 18. Neutral conductor to earth spacing and admittance of each D.T. load cut in half.

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\*also done on 1/4 wavelength network

19. Miscellaneous conductors added and admittance of each D.T. load cut in half.
20. Triplex neutral conductor and admittance of each D.T. load cut in half.
21. Spacer cable configuration and admittance of each D.T. load cut in half.
- \*22. Number of sections reduced by aggregation
- \*23. Number of sections reduced and admittance of each D.T. load doubled.
- \*24. Temperature
- \*25. Earth resistivity
- \*26. Neutral not assumed grounded
27. Total length varied  $\pm 5\%$ .
- \*28. Earth resistivity varied for cable feeder
- \*29. Temperature varied for cable feeder
- \*30. Number of sections reduced by aggregation for cable feeder
- \*31. Admittance of each D.T. load doubled for cable feeder
- \*32. Admittance of each D.T. load cut in half for cable feeder
- \*33. All D.T. loading neglected for cable feeder
34. Total length varied  $\pm 5\%$ .
35. Aggregation tested on a description of an actual feeder

\*also done on 1/4 wavelength network

nature of a variable permitted, normalized sensitivity ratios\*\* were computed. For binary items (for example a basic change in line configuration such as OH cross arm vs. spacer cable construction), the decimal percent change in eigenvalues and characteristic admittance were noted.

The effect of all items on propagation were "investigated" by demonstration, using two hypothetical networks, and computing the corresponding changes in the input driving point admittance matrix and voltage transfer ratio from input to end, and as before, for one at a time variations in the items mentioned above. Also as before, where appropriate normalized sensitivity ratios were computed. The two hypothetical networks were simple unbranched uniform three phase lines, with uniformly located constant size distribution transformer loading cyclically connected to the feeder phase conductors. Also, a terminal end three phase load was applied. These distribution transformer loadings and terminal load were selected to represent a plausible loading density. The specific details of these hypothetical nominal networks are shown in the following Table (3)(A)-2. The "nominal" overhead (OH) was conventional cross arm while the underground (UG) was three single phase cables with a propagation speed of approximately .35 speed of light.

The input driving point admittance (DPA) was examined because if such a line were a branch-lateral, its affect on the remainder of the network is, of course, entirely determined by this DPA. In order to

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\*\*relative change in the dependent variable divided by the relative change in the independent variable.

Table (3)(A)

Hypothetical Test Network Characteristics

	<u>OH #1</u>	<u>OH #2</u>	<u>UG #1</u>	<u>UG #2</u>
Frequency	8.13 kHz	8.13 kHz	8.13 kHz	8.13 kHz
Total Length*	16000M	8800M	16000M	3400M
Electrical Wavelength	$\approx .45\lambda$	$\approx .24\lambda$	$\approx 1.25\lambda$	$\approx .26\lambda$
DT Loading**	-78 DB -27.3° for all (nominal)			
DT Spacing	200M	110M	200M	42.5M
Number of DT	80	80	80	80
Terminal Loading	All three phase wye $4.77 \cdot 10^{-4}$ mhos -68.2° each phase			

\*Unbranched uniform three phase

\*\*Cyclically assigned to phase conductors

provide some visual insight into voltage propagation, plots were made of the magnitudes of the three phase voltages versus distance from the source. Also, the algebraic sensitivities associated with the terminal end voltages were also tabulated.

The voluminous results and conclusions of this study are contained in Volume 2, Chapter (3)(A). It can be appreciated that such an investigation as this must at best be finite and in this study, consisted only of a demonstration based on a few network examples. The effects of parameter variations on other networks may not be similar. Hence, these results are considered only demonstrations and are offered as some qualitative guide. Many other demonstration situations have not been examined and experience by users will have to be accumulated.

The following are some very generalized observations (not itemized in any particular order). It should be noted that the qualitative assessments to be followed are guided by the notion that for communication purposes, 3 db represents a reasonable threshold to judge an effect significant or not significant.

- 1) Commonly encountered phase conductor diameters could be "graded" into two or three sizes with satisfactory results.
- 2) Reasonable variations in conductor spacing are not significant. However, radical changes in OH construction (say, for example, cross over vs. spacer cable) can be significant for sufficiently long lengths (how long is long, has not been evaluated).
- 3) Spacing between neutral and phase conductors (DH) may be significant.
- 4) The shielding effect of miscellaneous conductors seems to usually be insignificant.

- 5) OH line loading can have significant voltage propagation effects so that changes in the average levels of DT secondary loading need to be investigated parametrically.
- 6) Three phase loads can significantly effect propagation.
- 7) Loading of UG lines by DT's has negligible effect on voltage propagation.
- 8) Variations in feeder loading will, of course, have strong relationship to input driving point admittance.
- 9) Whether or not the neutral is analytically assumed at ground potential (DIFNAP IASM option) is insignificant (as expected) for voltage drives involving the feeder phase conductors.
- 10) Fractional (factor) uncertainties in total line length are to a good approximation equivalent to the same fractional change in frequency. Line length uncertainties can have significant effects.

Assuming that the basic topology of a feeder network is known (disconnect, tie, reclosure switches, etc) and a reasonable identification of line configurations has been made, the principal sources of model prediction errors seems to be apriori uncertainties in:

level of feeder loading

length of lines.

The first requires a parametric model evaluation to ascertain "worst case" considerations. The second requires care in specifying line lengths and probably making "neighborhood" frequency response predictions to observe what possible effects length errors may have, or equivalently parametrically varying the various line lengths.

### Task (3)(B) Parameter Sensitivity "Set-up" Time Reduction

The purpose of this task was to investigate what reasonable approximations could be made to decrease the time required to prepare network data base files and network files before actual propagation predictions can be initiated.

It is appropriate to distinguish between the preparation of data base files and network files. Ideally, as time progresses, the data base files will become more and more complete as they are augmented with catalogued items. For example, at this time, a reasonably extensive inventory of OH and UG line configurations have been catalogued and included in the LTYP DATA (See Chapter M of this volume) so that as new applications occur, it is probable that it will contain already most of the required configurations so that any required augmentation will be small. Similarly, for the data base file containing distribution transformer data. The data base files for three phase loads is not so complete so that it can be expected that more work would be required to augment this file, especially since at this time\* lumped parameter models are not used therein, requiring construction of admittance data at any new application frequency. However, it is clear that as each new application is encountered, it can be expected that less and less time will be required to establish the data base files. Finally, note that with

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\*Some limited effort has been applied in the direction of using lumped parameters for certain apparatus.

the present implementation data base files associated with line configuration and distribution transformers are easily generated for any new frequency of interest and involves only trivial effort.

Generating the network file representing symbolically the network is, of course, unique to each application area.

The sensitivity analysis of Task (3)(A) can be of help in reducing the effort to augment the data base files by offering guidelines for grading the encountered line types into either existing catalogued varieties or reducing the number of new varieties that need to be added. Also, the sensitivity analysis combined with "DT aggregation" to be explained below, may again offer guidelines to reducing the number of sections (lines/records in the network files) necessary to adequately represent the feeder. However, to do this would require (rather simple) modifications to present procedures to allow more than one DT to be assigned to each section, i.e., DT aggregation mentioned above. The approximation involved in DT aggregation have been investigated in this task.

The approximation due to DT aggregation have been investigated to the extent that reasonable degree of aggregation introduce very little approximation. The limits to which this can be carried have not been established. The idea of DT aggregation was applied to an actual feeder (NMPC 34556) by reducing each occurrence of cascaded sections of identical line type to a single section of same total length and all DT's in the cascade located together at the terminal end of the equivalent single section. In this application, the number of sections was reduced by approximately 37% with negligible error



(as compared to the original more detailed representations).

Again, as stated above, criteria to guide how far this can be done has not been fully developed.

Based on this observation, it is recommended that after sufficient confidence has been established in the model, and assuming the need exists, that the rather minor program modification be made to allow more than one DT to be assigned to a section.

#### Task (4) Transformer Modelling

This task was concerned with the modeling of two winding transformers in the context of use at PLC frequencies. Distribution transformers are included in this category by assuming them electrically symmetric and having balanced secondary loads with the net result they become effectively two winding transformers.

The purpose behind the effort was to obtain a suitable computational model which would lead to an automated software procedure (not requiring manual intervention) for predicting two-way propagation through the transformers, i.e., from primary to secondary and secondary to primary. Also, with such a model, the effect of different levels of secondary loading (deterministic and random, i.e., MONTE CARLO) could be easily accomplished. From a system engineering point of view, PLC propagation through transformers represents a critical item in system performance and having a physical model is very useful for understanding these limitations and the effect of possible fixes such as tuning and bypass procedures.

Transformers of interest are:

Distribution Transformers (assuming electrical symmetry and balanced secondary loading)

Single Phase (most are) Ratio Bank Transformers

Three Phase Transformer Banks (Three Single Phase Transformers) including open delta banks.

Single Core Three Phase Transformers were not considered.

#### Synopsis of Phase I Transformer Modeling Activities

Transformer modeling was initiated in Phase I of this project. At that time, little previous apriori knowledge existed regarding the

behavior of distribution transformers at PLC frequencies and, in particular, when the various higher order levels of distributed/stray capacity became important. Also, it was originally intended that models be developed for frequencies to 500 kHz. Therefore, it did not appear that an analog type lumped parameter model could be developed and an associated parameter data base established within the time, available manpower, and funding constraints associated with the Phase I effort. Therefore, it was decided to use measured "Y" parameters which would be frequency dependent (and of course KVA and other constructional features) but otherwise completely general. This approach was encouraged by several references on the subject.\*

Therefore, concurrent activities of measurement, and model development and software implementation were initiated. An extensive set of "Y" parameter measurements\*\* were made on 5, 10, 15, 25, 50 KVA distribution transformers for frequencies to 500 kHz. Subsequently when attempting to use these measured "Y" parameters, significant inconsistencies were discovered. After much deliberation, it was hypothesized that the "Y" parameters must be measured/determined with an accuracy and precision that was not realized and would probably not be practical even with more sophisticated procedures.

By the time this conclusion was reached, only limited resources and time remained. In order to temporarily overcome this problem, a procedure was implemented using a file containing measured primary driving point admittances (for specified level of secondary loading).

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\*See pgs. 635-641 "Magnetic Circuits and Transformers" MIT EE Staff, John Wiley & Sons.

\*\*Six "Y" parameters plus an open circuit impedance.

This allowed predictions to be made on the feeder for the specified loading implied in the transformer file being used. Prediction "down to" the secondary would be a second manual step using again measured voltage transfer characteristics. This "two step" procedure was not in any way deficient as an approximation, but did require manual interaction and did not admit random "MONTE CARLO" procedures.

#### Synopsis of INTERPHASE Transformer Modeling Activities

During the approximately one year interval between the conclusion of PHASE I contract effort and the commencement of this PHASE II contract, the General Electric Co. sponsored extensive response type measurements on distribution transformers, single phase power transformers, and various single core three phase transformers. These measurements were made at (GE) Corporate Research and Development with the cooperation of the Niagara Mohawk Power Company who provided access to the various transformers, and (GE) Mobile Radio Department. The measurements included bi'directional driving point admittance and voltage transfer ratios as a function of frequency (limited range) and various loadings (primary and secondary). It was from these measurements that adequacy of a single RLC lumped parameter model for frequencies up to, say, 50-100 kHz, was suggested.

#### Synopsis of PHASE II Transformer Modeling Activities

Still faced with need and solution for an adequate transformer model, this activity was continued as Task 4 in the PHASE II contract. Four modeling approaches were considered:

- 1) All "Y" parameter model (as in PHASE I) with greater measurement precision.

- 2) "Y" parameter derived algebraic model
- 3) Table look-up of measured responses
- 4) Simplified lumped parameter model

Approach 1) was rejected because of the reasons cited previously and the uncertainty whether sufficient measurement precision could be obtained. Approach 3) was rejected (after 2 and 4 appeared feasible) because of the large number of interpolating dimensions (frequency, magnitude of loading, primary and secondary, phase of loading) and the prohibitively large amount of measurements required.

During the above deliberations, an algebraic basis was developed, corresponding preliminary measurements were made, and a computer program written to establish the feasibility of approach 2). Appendix 3 contains analyses relevant to this approach. The key difference between this approach and the "Y" parameter approach 1) was to assume that:

- a) at frequencies of interest, distribution transformers are electrically symmetric (two secondary windings),
- b) a balanced secondary load (no basis exists for assuming otherwise for purposes of PLC propagation modeling),

and to replace some of the "Y" parameters with other more readily and algebraically less sensitive measurements such as open circuit voltage transfer ratios. As a result of laboratory measurements on several transformers, a set of derived parameters were selected which were relatively insensitive to transformer construction. The resulting algebraic model was implemented in a temporary test (computer) program which very successfully predicted responses corresponding to measurements. The feasibility of this approach appears to be proven. Like "Y" parameters, these derived parameters would be frequency and KVA

dependent but independent of loading, and would predict bi'directional driving point admittances and voltage transfer ratios. It does not appear that this model has any frequency limitations (other than measuring them at such frequencies). It does not, of course, represent a physical model.

Measurements (see last page of Appendix 3) made during the INTERPHASE interval strongly suggested that a simple RLC lumped parameter model might be adequate for frequencies limited to, say, less than 50-100 kHz. A test computer program was written to evaluate the model and quite successfully duplicated the measurements cited above. On this basis, subject to the limitations on upper frequency, the simplified lumped parameter model also became a viable contender. It should be noted that it is realized a more complicated lumped parameter model could be derived to extend this frequency limitation, but doing so at this time is not considered necessary.

#### Results of PHASE II Transformer Modeling Activities

Several sets of distribution transformer data have been compiled:

- i) PHASE I "Y" parameters
- ii) INTERPHASE response measurements as a function of load
- iii) INTERPHASE measurements by the (GE) Mobile Radio Dept.
- iv) PHASE II parameter and response measurements

The last set constitutes the most detailed for the purpose of establishing and choosing a model. Based on the selection of candidate modes 2 and 4 (above), the following measurements were made during this PHASE II:

### Parameter Measurements

- a) L-L admittance "looking" into secondary, primary short circuited.
- b) Transadmittance; voltage applied to primary, currents measured in short circuited secondary, and vice versa.
- c) Primary admittance "looking" into primary with secondary short circuited.
- d) L-L admittance "looking" into secondary, primary open circuit.
- e) Primary admittance "looking" into primary, secondary open circuited.
- f) Open circuit voltage transfer from primary to secondary (2-2).
- g) Open circuit voltage transfer from secondary (L-L) to primary.

### Response Measurements to Verify Model

- h) Primary admittance "looking" into primary, secondary resistively loaded at various fractional per unit loads.
- i) Secondary admittance "looking" into secondary, primary resistively loaded with 10, 10<sup>2</sup>, 1000 ohms.
- j) Primary to secondary voltage transfer ratio with secondary resistively loaded as in h) above.
- k) Secondary to primary voltage transfer ratio with primary resistively loaded as in i) above.

The magnitude and phase were determined for each of the above and recorded graphically as a linear function of frequency from 2.5 kHz to 100 kHz.\*

Also, while the above measurements were being made, a computer program ZPTRANS1 (see Appendix 4, Volume 3) was written incorporating the proposed simple RLC lumped parameter model. This program generates "ZETA" X-Y plots of the magnitude and phase for each of the above

\*Various other miscellaneous items were also measured.

response measurements and with the same dimensional scaling so that the measurements and predictions can be physically compared by overlaying on one another.

These comparisons indicate that the simple lumped parameter model was quite adequate for frequencies, say, to 50 kHz. Volume 2, Chapter "TASK (4)", has a more detailed account of these comparison and modelling details. Based on these results, and assuming the model is not used beyond 50-100 kHz, it is recommended that the simple RLC model be adopted. Obviously, as a lumped parameter physical model, it affords a physical insight and also implicitly contains frequency dependency so that one set of RLC parameters suffice for all frequencies, simplifying file structures and easily adapting to automatic frequency response calculations.



### Task (5) Line Compensation and Termination Techniques

This task was concerned with investigating techniques to minimize the adverse effects, when encountered, due to phenomenon related to the "transmission line" characteristics of feeder sections, branches and lateral. Based on limited examples examined at this time, it appears that the most frequently encountered adverse effect is due to low impedances that sometimes can be presented the feeder by low impedance laterals that occur by virtue of their resonance or low characteristic impedance, such as cables which have a high capacity per unit length. Less frequently occurring is the possibility of standing wave minimum on long feeder runs with light loading.

Up until recently, when this model became operational, the only evidence that the application engineer would have regarding these kinds of situation/problems occurred after some sort of limited deployment trial installation or some sort of field measurements also usually, for practical reasons, limited in the number of observation locations. Prior to realizing and understanding the nature of these problems, it was difficult for the same reasons to even identify reasons for the difficulties.

Therefore, the problem is two-fold; 1) to identify potential or actual problem locations, and 2) to devise possible corrective procedures, and of particular interest herein, techniques of line compensation.

To assist in the first problem of identifying potential problem areas the model software was augmented to include an output profile option which presents for each section comprising the network a set

of easily scanned data. The data items presently selected for display are:

SEC	Section number
SIB	Sibling number (if present)
PAR	Parent number
CUMDIST	Cumulative distance from source
$ V_1 ,  V_2 ,  V_3 $	Phase voltage magnitudes
ZTR/MIN	The maximum impedance magnitude seen looking individually between each phase conductor and neutral.
VF	Voltage flag (set when a user defined threshold exceeds the magnitude of each phase voltage)
ZR	Impedance flag (set when ZTR/MIN is less than a user defined threshold)
YINMX	The reciprocal of the largest element magnitude in the input driving point admittance for the section.
YSIBMX	The reciprocal of the largest element magnitude in the input driving point admittance of its sibling section (if present)
YNORMX	The reciprocal of the largest element magnitude of the equivalent Norton's source admittance looking backwards from the input of the section.
SIB/*	Ratio YSIBMX/YINMX
SIB/N	Ratio YNORMX/YINMX
GRAD	Maximum element magnitude in section output voltage vector minus input voltage vector all divided by the section length.
POWER	Power level

The user can easily replace any of the above by others of his choice. The items VF and ZF are useful to quickly locate trouble spot areas. The other quantities are useful to pinpoint problem sections. Obviously many of these items are correlated.

The above type of scan profile for the entire network has proved very useful for identifying the location and nature of "trouble spots". Limited experience to date seems to indicate that "trouble spots" seem to be related to laterals with low impedance, due to resonance or low intrinsic characteristic impedance (cables).

In the cases so far examined involving low impedance laterals "joining" high impedance (overhead) feeder construction, the impedance level of the lateral can be raised by various types of shunt (inductive) compensation, both terminal and distributed. For monochromatic systems, many compensation circuits and locations are possible and an approach is described in the detailed report on this subject contained in Volume II, Task (5). With broadband system requirements distributed compensation appears desirable.

The detailed reports in Volume II for Subtasks (1)(B), (1)(C) describe some actual results obtained using simple compensation.

## J. Conclusions and Observations

This section is a summary assessment of the restrictions, assumptions and scope of the model at this time. Figure J-1 presents a list of fundamental restrictions associated with the current model and implementation. As noted, items 2 and 3 are not essential restrictions. Figure J-2 presents a list of engineering assumptions implied in the model.

As a result of experience gained during this PHASE II effort, the conclusions and observations are made:

### a) Uncertainties in apriori knowledge of line lengths

Since, as a reasonable qualitative approximation, the parameters frequency and line length appear in the various mathematical formulae as a product pair, errors in the apriori knowledge of line length effect propagation in corresponding similar fashion as a change in frequency. In particular, errors in line length represent a higher fractional wavelength as the frequency is increased.

If our verification experiences are considered typical, then the model should be used with caution for frequencies greater than (say) 25-50 kHz. If line lengths are known with correspondingly higher accuracy, then this limit can be increased, of course, subject to other limitations mentioned below.

As a result, it is recommended that a parametric variation investigation on frequency or length be made in the neighborhood of the apriori values to determine the possibility of any severe resonance phenomena being missed due to apriori errors in line length.

b. Transformer Secondary Loading Variations

Model based studies have indicated that propagation on the feeders can be significantly effected by the normal variations in loading presented to the feeder by transformers whose secondary loading varies as a natural circumstance. Hence, it is recommended that this affect be investigated via the model by parametric variation of the transformer secondary loading.

c. "Set-up" Time Required to Make Analysis Can be Reduced (some)

Results of the PHASE II Parameter Sensitivity Task has indicated that the detail and effort to prepare the DNWKINij file can be reduced, primarily by distribution transformer aggregation and line type (configuration) grading. That is by using, judiciously, a fewer number of distinct line types than may be actually encountered on a feeder and aggregating several transformers so as to be located at fewer numbers of distinct locations than may be actually encountered on the feeder, the number of sections required to represent a feeder may be greatly reduced. This in turn would similarly reduce the number of line entries required to prepare the DNWKINij network files.

Classification and the development of a lumped parameter data base file for the various types of transformers and their loads would greatly reduce the effort to establish data base load files as is presently required. The distribution transformer modeling Task 4 PHASE II is an example.

As further experience is obtained, it may be possible to further reduce the set-up time by apriori absorbing or neglecting very (electrically) short line segments and representing underground laterals with appropriately sized lumped capacitors.

d. Uncertainties in Substation Admittances

In those cases of model prediction of propagation, such as inbound, which involve a substation will usually require some sort of estimate for its equivalent load admittance. For transmissions from the substation (outbound) it is usually implied that the transmitter has sufficient drive to "force" design voltages to occur on the buss so that in this case the substation buss admittance is not involved in the propagation calculations. However, for inbound reception at the substation (or elsewhere) the substation represents a significant termination admittance. Whether the receiver operates on voltage and/or current signals, the substation admittance will be a significant "factor" in reality and modeling predictions.

Obtaining an estimate for the substation admittance load to be used in the modeling predictions is at the present time somewhat of an "unknown". The substation buss admittance is obviously effected by:

- a) other feeders connected to the buss
- b) substation transformers and the "source" admittance seen by them looking back into the subtransmission network,
- c) other station equipment.

At this time it is believed that a) can have a significant effect on the total admittance. Conceptually, these other feeders could be modelled to obtain predicted driving point admittances. Obviously that procedure has practical drawbacks.

Our experience to date has been limited to the NMPC Grooms Road Substation. For that substation we learned that it was necessary to measure the complete driving point admittance looking into the buss "from the" NMPC 34556 feeder. Due to the generally (expected) high admittance and physical construction, it was very difficult to make these measurements; many specialized procedures were used.

Hopefully future applications will allow other substation admittances to be measured to obtain some better appreciation. However, unless these measurements somehow lead to a reasonably reliable estimation procedure, it is likely that inbound predictions will be greatly influenced by uncertainties in substation admittance estimates. It is noted that "real life" receiver performance will similarly be affected. For this reason it is possible that receiver system designs many include procedures to minimize this variability and then, of course, the model predictions will correspondingly be less sensitive to these uncertainties. It is also felt that despite these uncertainties, a limited parametric variation or "worst case" prediction could still be useful.

Figure J-1

Fundamental Restrictions

- 1) No grid type networks including interconnected loops
- 2) Single source (for now)
- 3) No geometrically paralleling feeder circuits (for now)
- 4) Continuous neutral conductors through sectionalizing switches are assumed at zero potential at such points.



Figure J-2

Engineering Assumptions

- 1) Linearity
- 2) Affects of minor apparatus ignored
- 3) No conductive coupling between feeder phase wires except possibly by loads
- 4) Radiation losses ignored
- 5) Overhead conductor sag ignored
- 6) Underground cables laid with uniform spacing
- 7) Simple approximation for miscellaneous cables such as telephone
- 8) E-M field effects at geometrical discontinuities neglected
- 9) Miscellaneous conductors at zero (ground) potential
- 10) Carson's approximation assumptions

specifications for overhead lines and generates, in a specific format described in PHASE 1, Vol.2, the matrix Z and Y parameters for that line. Any equivalent line parameter program could be used for this purpose.

A synopsis of the capabilities presently included in the model implementation are shown in Table K-1. Some comments are in order to explain the "two step" procedure for primary  $\rightleftharpoons$  secondary propagation. Because the distribution transformer analytic model (IOPC = 0, 1, 2) is not implemented in software, a two step procedure is required to predict propagation to and from the secondary circuit. To illustrate, consider the procedure required, now, to predict propagation from a source on the feeder (say a substation) to the secondary of a particular distribution transformer (DT) or perhaps to an actual residence service entrance. First, the (assume balanced) load on DT secondary is determined by assuming individual house loads and analyzing the secondary circuit (electrically short and an easy analysis). Either using the analytic model or measured DT response characteristic for that secondary load and frequency of interest, determine the input (to primary) driving point admittance (DPA) which will tend to be dominated by the leakage reactance. This DPA then is placed in an ASCII data base file. Actually, it is possible that precomputed standard DT DPA's (for each DT KVA and relative secondary loading) would be used. Then, the DIFNAP program is operated and will use this loading for that DT and correctly predict the voltage at the DT primary terminals, which then can be used "off line" to predict the secondary terminal voltage and subsequently the

## K. Status of Software

This section summarizes the status of the software and offers various pertinent comments.

### Source Program Files

Volume 4 of this PHASE II final report contains source listing of all programs generated as part of this work. All are written in FORTRAN, with most containing embedded explanatory comments and represent the most current version as of the date of the listing. Some listings contain additional annotation. Naturally, the software is in a continued process of evolution and refinement.

### Honeywell DPS-1

The programs mentioned above are designed for execution on a Honeywell DPS-1 computer system with a 4JS1 operating system. As such, various FORTRAN subroutine calls for I/O, file procedures (opening, detaching, access, etc.) and special control may be peculiar to this system. Furthermore, various special subroutines (Complex Matrix Inverse, for example) are local. Other routines such as EIGCC are contained in the IMSL library.

The present programs at any one execution require a maximum of 46K word core memory and no overlay or virtual memory procedures are used.

### Availability

Inquiries regarding the availability of these programs should be addressed through Mr. Carl Gilchriest (see Section E of this report). The only program not listed and not available is the proprietary program DISEM7S3. This program inputs geometrical and electrical

service entrance voltages. The procedure for the reverse direction is similar except that feeder loading of the DT primary terminal is obtained from the NTWKANSj analysis program so that the DT secondary to primary voltage transfer ratio and secondary DPA can be obtained.

Section L of this volume contains recommendations for the implementation of features that could be but are not yet implemented.

TABLE K-1

Capabilities Presently Included

WYE and DELTA connected feeder

Wye system can be operated with or without neutral at zero potential.

DELTA system depends on feeder transmission line capacitance to ground to establish phase to ground voltages.

Transitions 3:2, 2:1, 3:1

Three phase WYE to single phase (two conductor)  
DELTA not permitted at present but can easily be extended.

Transpositions

Single Phase Ratio Transformer Model & Logic

RLC model

Primary - Phase to Neutral

Secondary - Phase to Phase

Relies on downstream admittance to avoid singularity same as real life.

RBTRDATA - Ratio Transformer ASCII Data Base File

See NTWKERS4 listing for imbedded components

Open Delta Transformer Load Logic

All loads (other than DT) contained in Primary Load File

Power factor correction capacitors

Three phase transformer loads

Open Delta transformers

etc.

Distribution Transformer - Primary  $\rightleftharpoons$  Secondary Procedures

File of DT Admittances (IOPC = 3)

Frequency Code ITTY (kva), Scalar Phaser Admittance

See TRANADS4 listing for imbedded comments.

One file for each implied DT secondary loading

Correctly predicts feeder propagation

Off-line "two step" procedure for primary  $\rightleftharpoons$  secondary

Ignore DT (IOPC<0)

Automated analytic (RLC) model (IOPC = 0, 1, 2) not implemented.

See Section L of this report

Supporting Software

Main programs for generating random binary data base files.

UG line parameters program

Program aids for construction ASCII data base files

Prototype programs to compute three phase transformer bank models.

## L. Recommendations

This section is primarily concerned with offering recommendations for improving and extending the capabilities and convenience of the model software implementation.

### Model Extensions

- a) Implement Distribution Transformer Model
- b) Implement Capability For Geometrically Paralleling 3-Phase Circuit
  - Common Buss Drive
  - Non Common Buss Drive
- c) Implement Distribution Transformer Aggregation\*
- d) Develop and Implement Procedures for Introducing Dispersed Sources
  - Incoherent Noise Sources
  - Coherent Sources
- e) Extend and Implement Three Phase Load (RLC) Lumped Parameter Modeling
  - Including Bank and Common Core Transformers
- f) Extend and Implement Three Phase Ratio Transformers

### Data Base Catalog Extensions

- g) Develop Line Type Catalog - Picture Book Dictionary of Standard Types
- h) Develop Three Phase Load Catalog - Picture Book Dictionary of Standard Types
- i) Develop Distribution Transformer Catalog

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\*Can be done with present implementation using zero length sections.

### Streamline Main and Support Program Operation

- j) Streamline Interactive Conversation in Main Programs
- k) Merge DISEM753 and UGZYGES1
- l) Introduce More Automation

RLC Lumped Parameter Models  
(Implied Frequency Dependency)

Automatic Frequency Response Capability

Automatic Generation of Required Database Files

### Translate Software to a Popular Mini Computer

Continue Investigation to Determine Limits to Simplifying  
Network Representation



M. COPY OF "TUTORIAL OVERVIEW ..." FROM PHASE I SUMMARY  
FINAL REPORT

The following material is a copy, with some minor updating editing, of Section O, PHASE I, Volume 1-Summary Final Report. It is provided here for readers not previously familiar with this work.

O. TUTORIAL OVERVIEW TO MODELING FEEDER NETWORK  
FOR PLC PROPAGATION

(Os). Introduction

This overview is intended for the reader who is not well-acquainted with the subject of distribution feeder networks viewed as a PLC communication channel, nor with the work of this contract which is aimed at developing models and computational procedures for predicting PLC signal propagation on the feeder network. The discussions presented in this overview are based on visual aids and material prepared for the DOE/EPRI Review held June 9, 1978, in Detroit, Michigan.

A more complete review of the computational procedure and implementation is contained in Volume 2, which includes an introduction containing similar information as is presented here.

This project is concerned with developing the model and computation procedures for predicting the propagation of PLC voltage/current on a tree network structure from a source to destination, taking into account a variety of network features. See Figure OS-1.

The result of this development has been a general purpose "deterministic" model and computational procedure which is summarized on Figure OS-2.

**Solution Should Take Into Account:**

Tree Structure - Multitude of Branches  
3-Phase Wires  
Neutral  
Ground  
Paralleling Wires  
Distribution Transformers  
Secondary Wires/Loads  
Power Factor Capacitors  
Ratio Banks  
Regulators  
3:2, 3:1, 2:1 TRANSITIONS  
Transpositions  
Etc.

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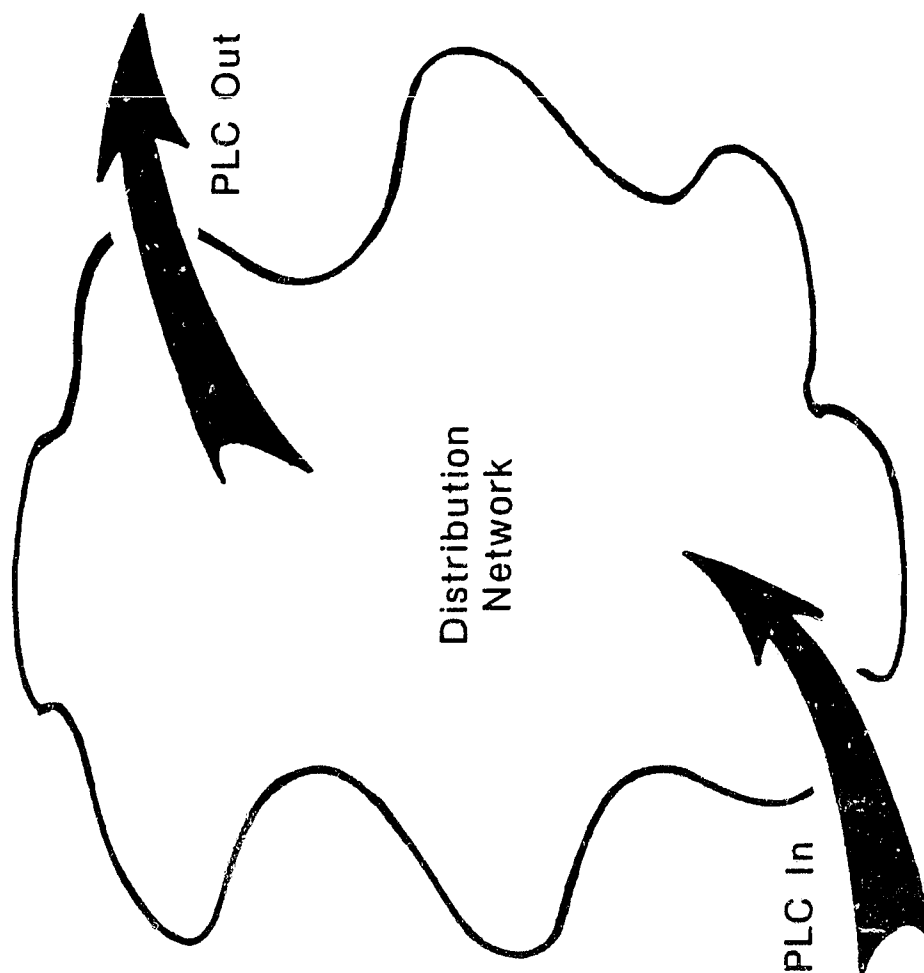


Figure OS-1. The Problem

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- (1) Two-Step Procedure to Calculate PLC Propagation on a Feeder Network with a Tree Configuration.

Step 1 - Perform Admittance and Voltage Transfer Matrix Reduction Inbound from Tree Tips Towards Source

Step 2 - Compute Voltage, Currents, Power, Outbound from Source to Specified "Node."

- (2) Structured to Take into Account Models for the Following:

Different Line Types

3:2, 3:1, 2:1 Transitions

3-Phase Transposition

Specified Feeder Load (Capacity Banks, etc.)

Ratio Bank Transformers and Voltage Regulators

Distribution Transformer Loading

Unlimited (Essentially) Levels of Branching  
and Number of Sections


Other Special Situations

- (3) Computes Using Vector-Matrix Procedures.

Figure OS-2. General Purpose "Deterministic" Model and Computational Procedure

(Od). Description and Representation of a Distribution Tree Network

The work of this contract is limited to distribution feeder networks which can be represented in tree form, as contrasted to a multiloop, highly gridded form. Figure OD-1 is a much simplified sketch of a typical local Niagara Mohawk Power Corporation suburban feeder network with a maximum distance from the Grooms Road substation of approximately eight miles. This network contains such features as overhead and underground feeders, three-phase to single-phase transitions, power factor correction capacitor banks (not shown), three-phase wye to three-phase delta ratio bank transformers, voltage regulators, considerable residential areas with both overhead and underground distribution transformers and secondary circuits, and other miscellaneous apparatus.

The top half of Figure OD-2 is an illustrative schematic of a segment of a feeder tree network, and shows the decomposition into "sections."\* This schematic illustrates a three-phase wye feeder with its neutral conductor, and an illustration of a three-phase to one-phase branch/transition. Also shown by the notation  are attached loads which represent single-phase loads, such as distribution transformers, and three-phase loads, such as capacitor banks, or the net effect of a three-phase branch. The bottom half of Figure OD-2 illustrates a symbolic representation of the same section using labelled section numbers. The notation



\*The use of the description "section" is synonymous with and supersedes the description "node" which was used earlier and may still appear on various computer program source listings.

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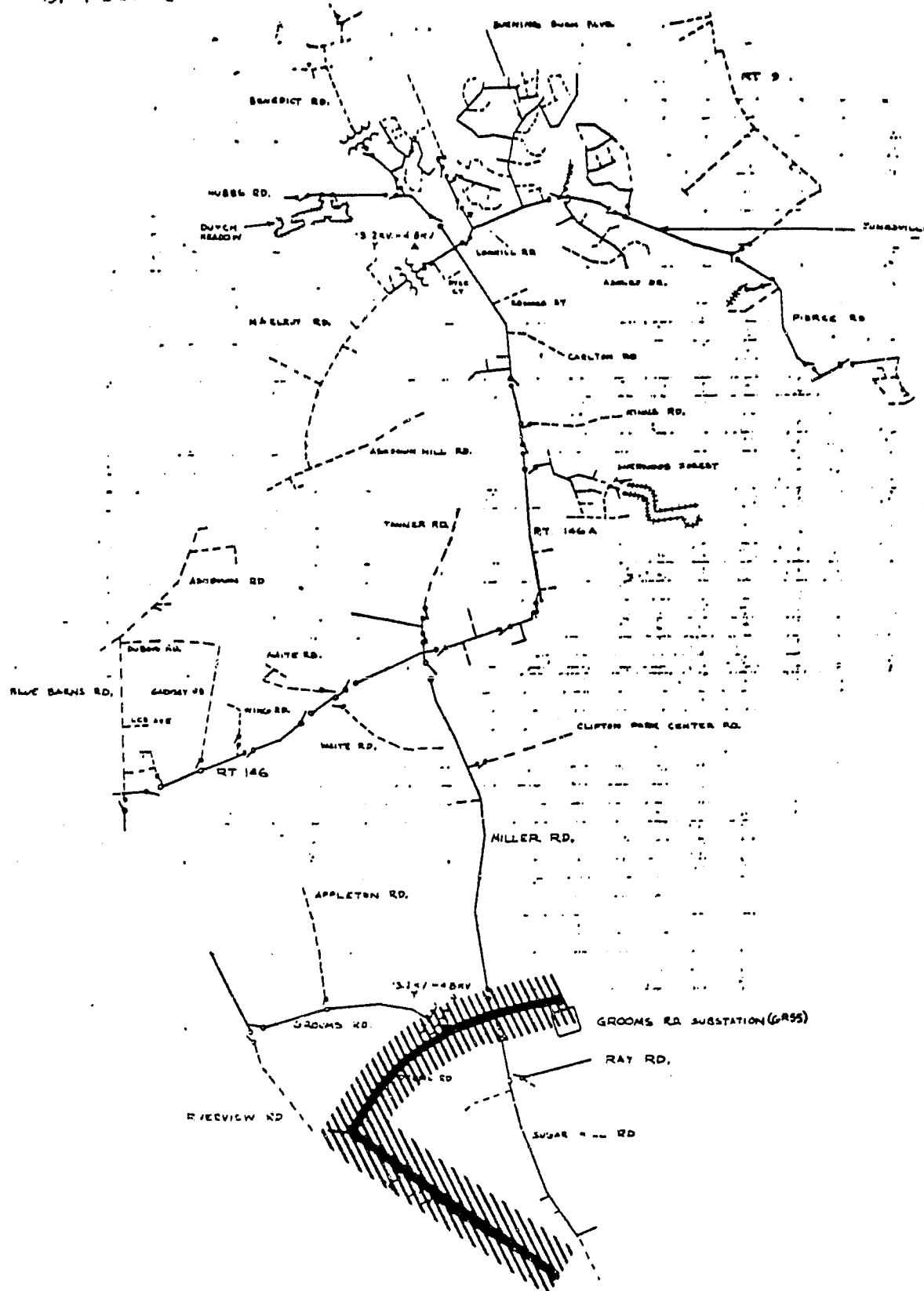


Figure OD-1. Network - Niagara Mohawk Power Corporation Feeder #34556

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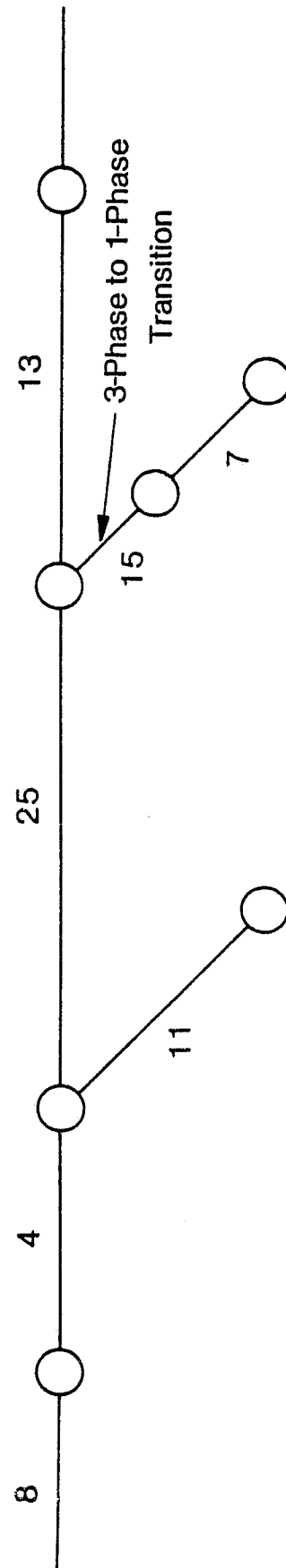
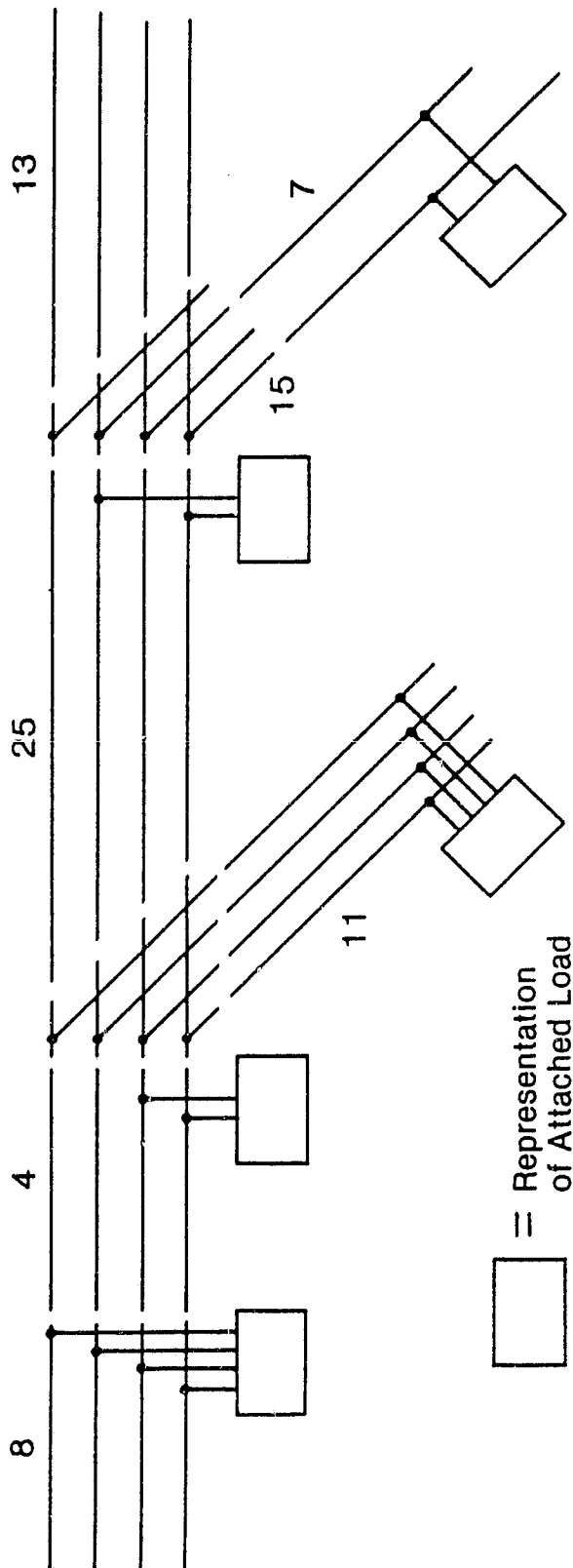


Figure OD-2. Illustration of Network Representation by "Sections"

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has been used for convenience to represent a section composed of a length (possibly zero length) of a homogeneous multiconductor line terminated by some sort of discontinuity, such as an attached load.

Figure OD-3 presents a formal definition of a "section," and Figure OD-4 gives examples of various section types. Later, an explanation will be given for a coding scheme that has been adopted to logically specify to the computer programs which type of section is involved at each point in the network.

Referring to Figure OD-2, which illustrated the idea of a "section" as an element in the network and also introduced a symbolic scheme for representing a segment in a network, consider Figure OD-5, which illustrates a small, binary tree network and its logical representation via a tabular format. The strategy is self-evident; however, a few comments are in order.

- (a) This tabular representation, which specifies for each section a parent section and can specify a binary branch in terms of an LSON (left son) and RSON (right son) section, completely determines a binary tree configuration.
- (b) Only one section will be a root section with a specified source at its input terminals. This is indicated by the zero in the parent column.
- (c) The assignment of section numbers can be completely arbitrary as long as they are not duplicated and represent a consistently defined network.
- (d) When a section is not followed by a binary branch, it is arbitrary which of the LSON or RSON entries are assigned to zero.
- (e) A terminus node is logically specified by zero in both the LSON and RSON entries.

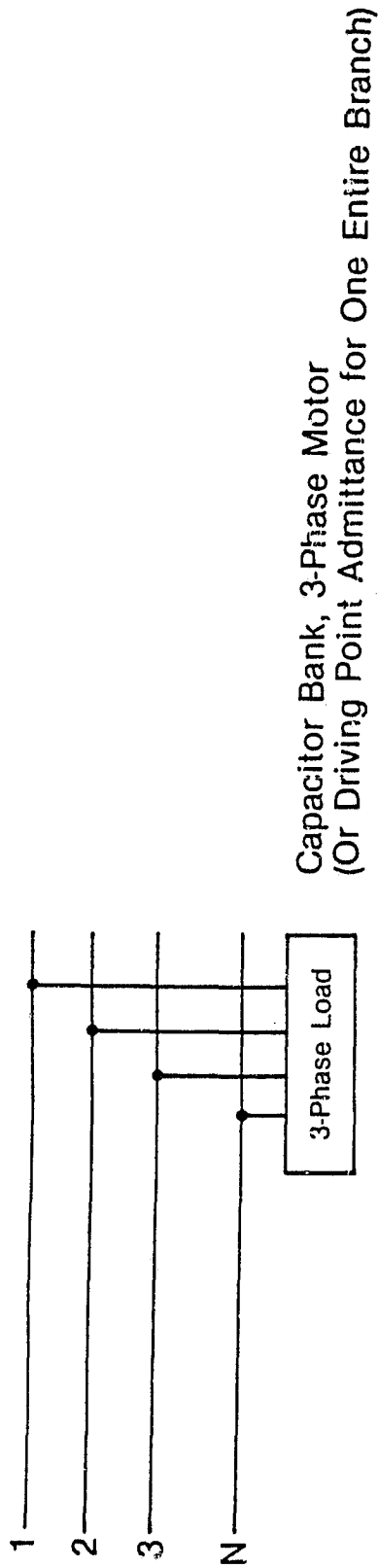
With this tabular representation, it is easy to determine the path from any section to the source (root section). It is also implied that ternary and higher order branching is not allowed. However,

**“SECTION” =**

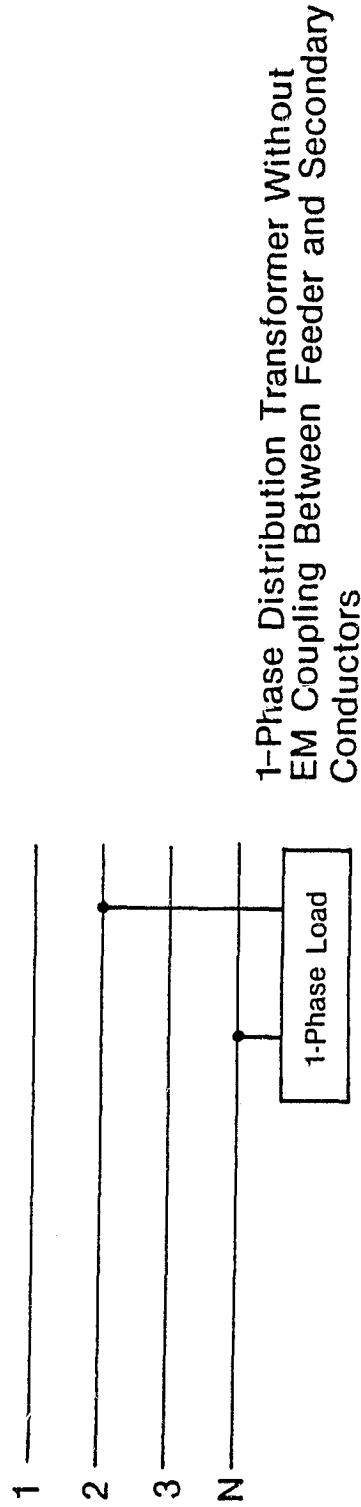
- 1) Length of Homogeneous Multiconductor Transmission Line Terminated by a Discontinuity Such as
  - Branching
  - Connected Load (including open circuit, i.e. end point)
  - Transition (3:2, 3:1, 2:1)
  - Transposition
  - Apparatus (such as Ratio Banks Transformers, Voltage Regulators, Auto Reclosures, etc.)
  - Special Conditions
- 2) Transition
- 3) Transpositions
- 4) Apparatus (through which signal must propagate)
- 5) Special Network Situations

Figure OD-3. Definition of Section





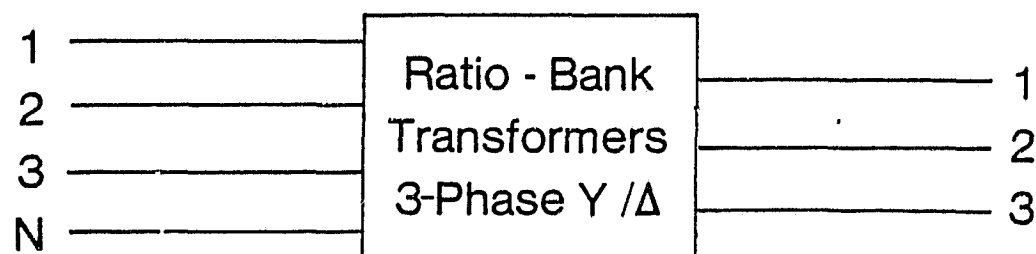
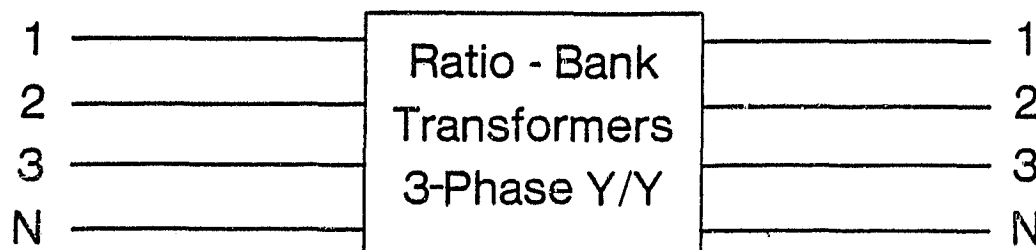
3-PHASE LINE 3-PHASE FEEDER LOAD



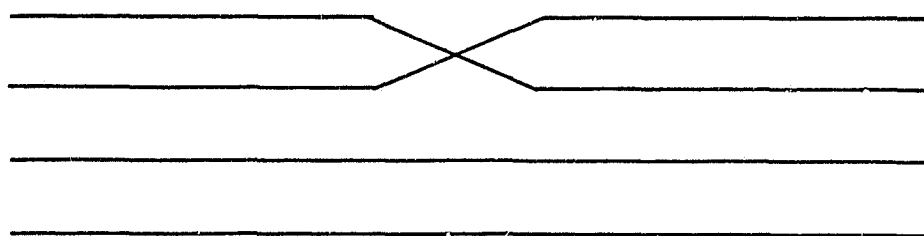
3-PHASE LINE 1-PHASE FEEDER LOAD

Figure OD-4. Examples of Sections

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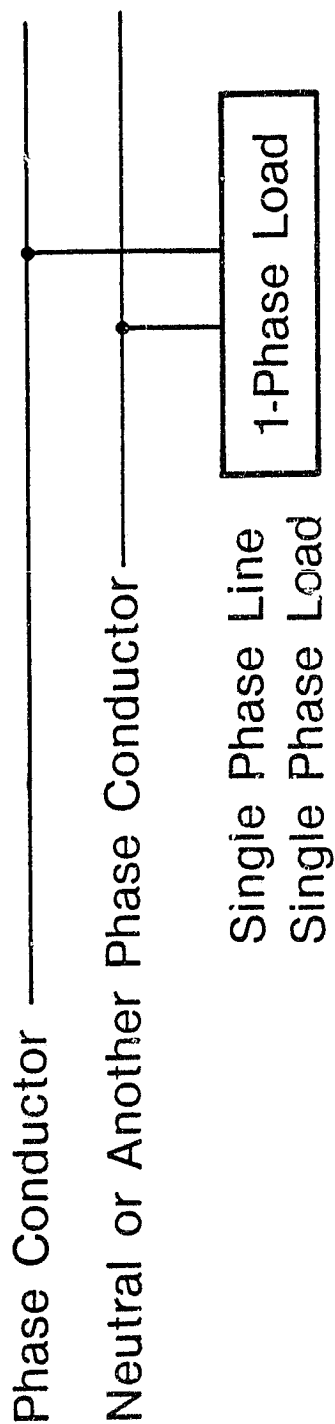
Similarly for Voltage Regulators  
Automatic Reclosures, etc.



3-Phase Transposition

Figure OD-4. Examples of Sections (Cont'd)

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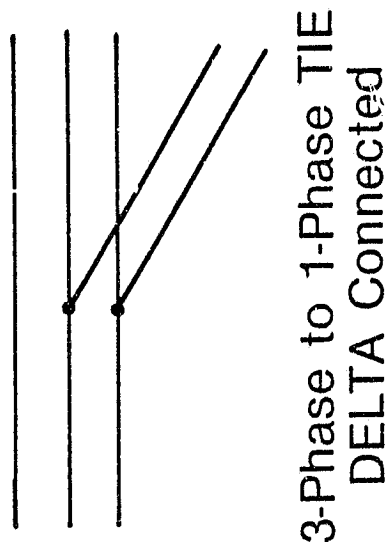
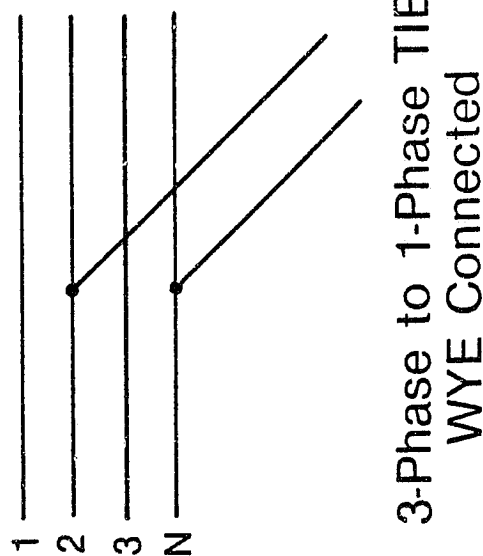
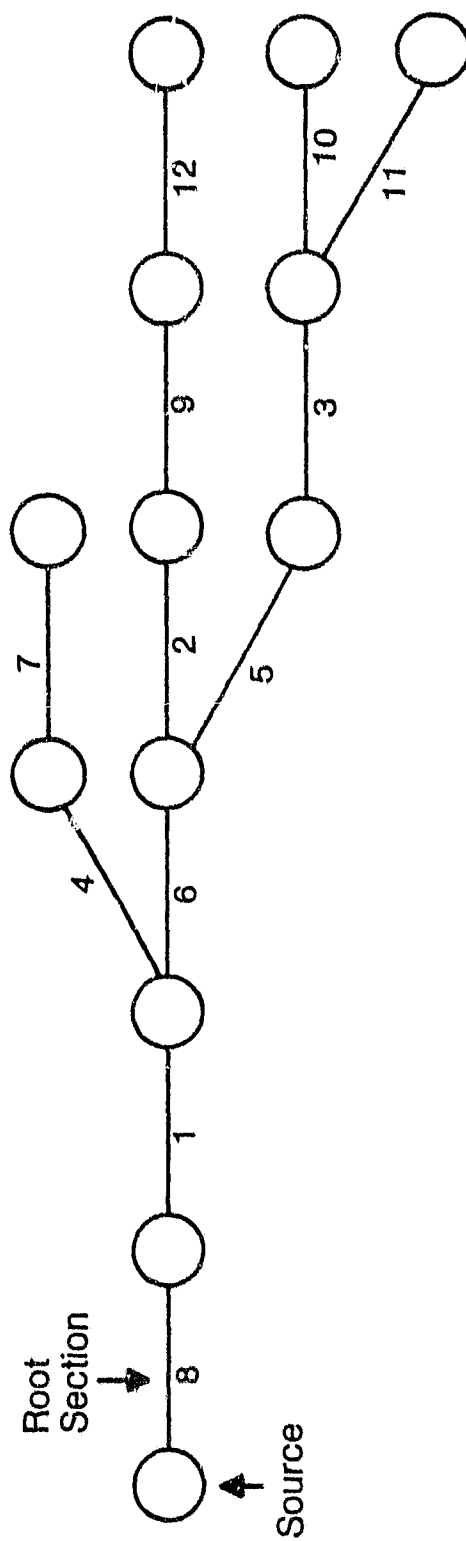


Figure OD-4. Examples of Sections (Cont'd)

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Section	Parent	RSON	LSON
1	8	4	6
2	6	0	9
3	5	11	10
4	1	0	7
5	6	0	3
6	1	2	5
7	4	0	0
Root Section → 8	0	0	1
9	2	0	12
10	3	0	0
11	3	0	0
12	9	0	0

Terminus Sections

Figure OD-5. Hypothetical Binary Tree Network and Its Representation

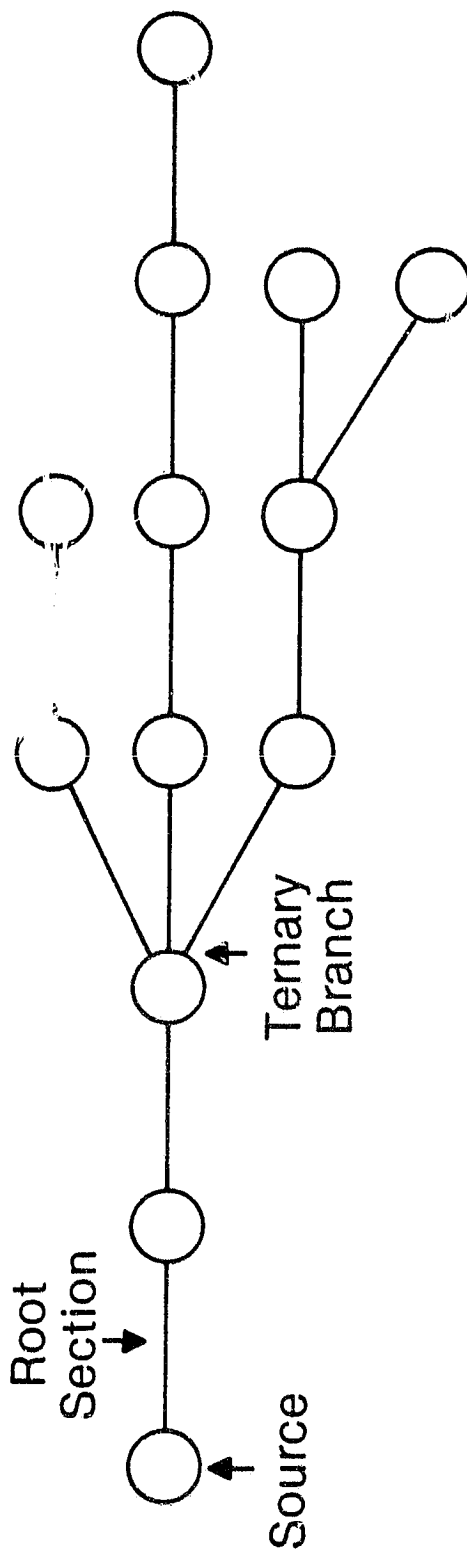
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this does not represent a limitation. if the concept of a "zero length" section is admitted. Figure OD-6 illustrates the use of a zero length section to expand a ternary branch into a sequence of two binary branches. The restriction to binary (branching) trees is not essential, but has been made to capitalize on the existing and extensively developed algorithms for determining processing sequences for binary trees.

In addition to the columnar data associated with the parent, LSON, and RSON sections, additional columns can and have been added to describe other characteristics of the network. Figure OD-7 specifies the columnar entries presently adopted for representing the network. Columns 1 through 5 (node  $\equiv$  section) are self-evident from the preceding discussion. Column 6 contains a line-type code (LTYP) number chosen according to the schedule shown in Figure OF 8. These line-type codes are used by the main network programs to properly control logic, and to address, as appropriate, various data files. Column 7 (Figure OD-7) is an integer number representing the length (in meters  $\times 10$ ) of the homogeneous line involved when  $100 \leq \text{LTYP} \leq 999$ . This interval (100,999) allows a maximum of 900 different transmission line type configurations to be identified in this manner. Figure OD-9 illustrates some overhead configurations and their assigned LTYP codes. In these sketches, 336.4 indicates wire size. M3 indicates a miscellaneous cable-type conductor, such as telephone or cable TV. This range of codes would also include underground cable configurations.

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## NON-BINARY TREE



## BINARY EXPANSION

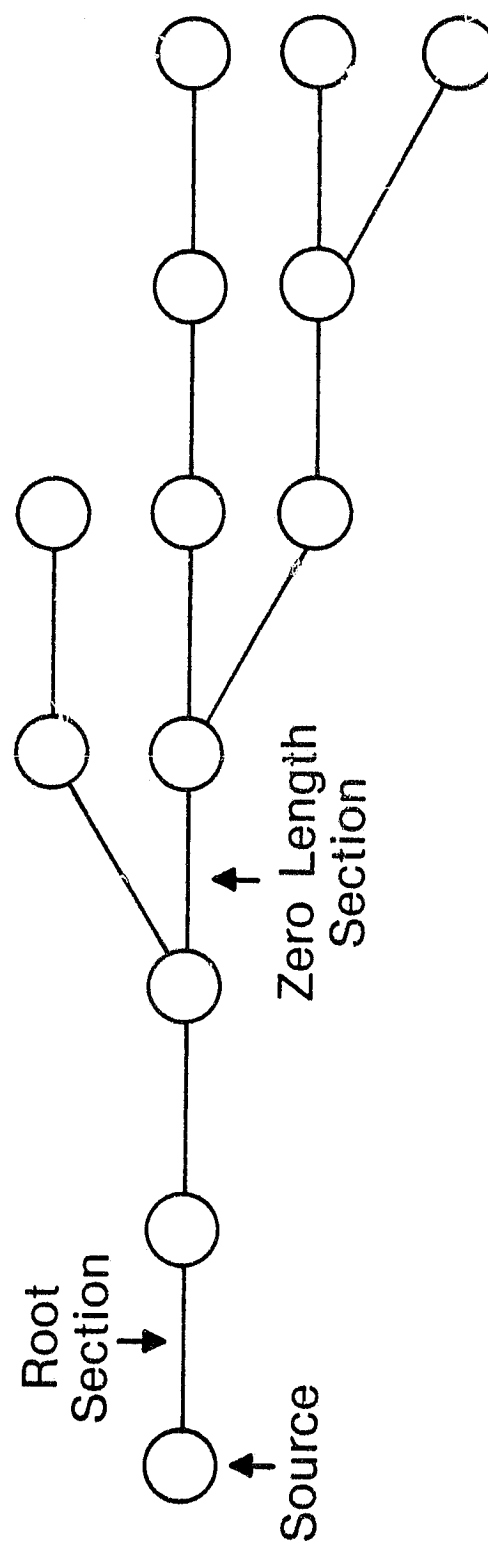


Figure OD-6. Expansion of Non-Binary to Binary Tree

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LTYP, ASSUMPTION CODE, IØPC CODE  
CONVENTION

1	3Ø → 1Ø	Y	Using Phase 1	and Neutral
2	3Ø → 1Ø	Y	" " 2	" "
3	3Ø → 1Ø	Y	" " 3	" "
4	3Ø → 1Ø	Δ	" " 1,2	(+ polarity sense)
5	3Ø → 1Ø	Δ	" " 1,3	(+ " " )
6	3Ø → 1Ø	Δ	" " 2,3	(+ " " )
7	3Ø → 1Ø	Δ	" " 2,1	(- " " )
8	3Ø → 1Ø	Δ	" " 3,1	(- " " )
9	3Ø → 1Ø	Δ	" " 3,2	(- " " )
12	Transposition Phase 1 and 2 interchanged			
13	"	"	1 " 3	"
23	"	"	2 " 3	"
24	3Ø → 2Ø	Y	Using Phase 1, 2 and Neutral	
25	3Ø → 2Ø	Y	" " 1, 3	" "
26	3Ø → 2Ø	Y	" " 2, 3	" "
27	2Ø → 1Ø	Y	" " 2 out of 1,2, and Neutral	
28	2Ø → 1Ø	&	" " 1 out of 1,2, " "	
29	Same as 27			
30	Same as 28			
31	Same as 28			
32	Same as 27			
33-39	Ratio Bank Transformers			

Assumption Code	Secondary Neutral	Secondary Conductors	Feeder Neutral	Misc. Cond.
1	0			0
2	0	0		0
3	0		0	0
4	0	0	0	0
5				0

IØPC Code

- 1 - Open Circuit      <0 - Ignore Transformer Loading
- 0 - Short Circuit
- 2 - Analytical Model      0-15
- 3 - Special Array      Figure OD-8. Line Type Code, LTYP,  
Schedule

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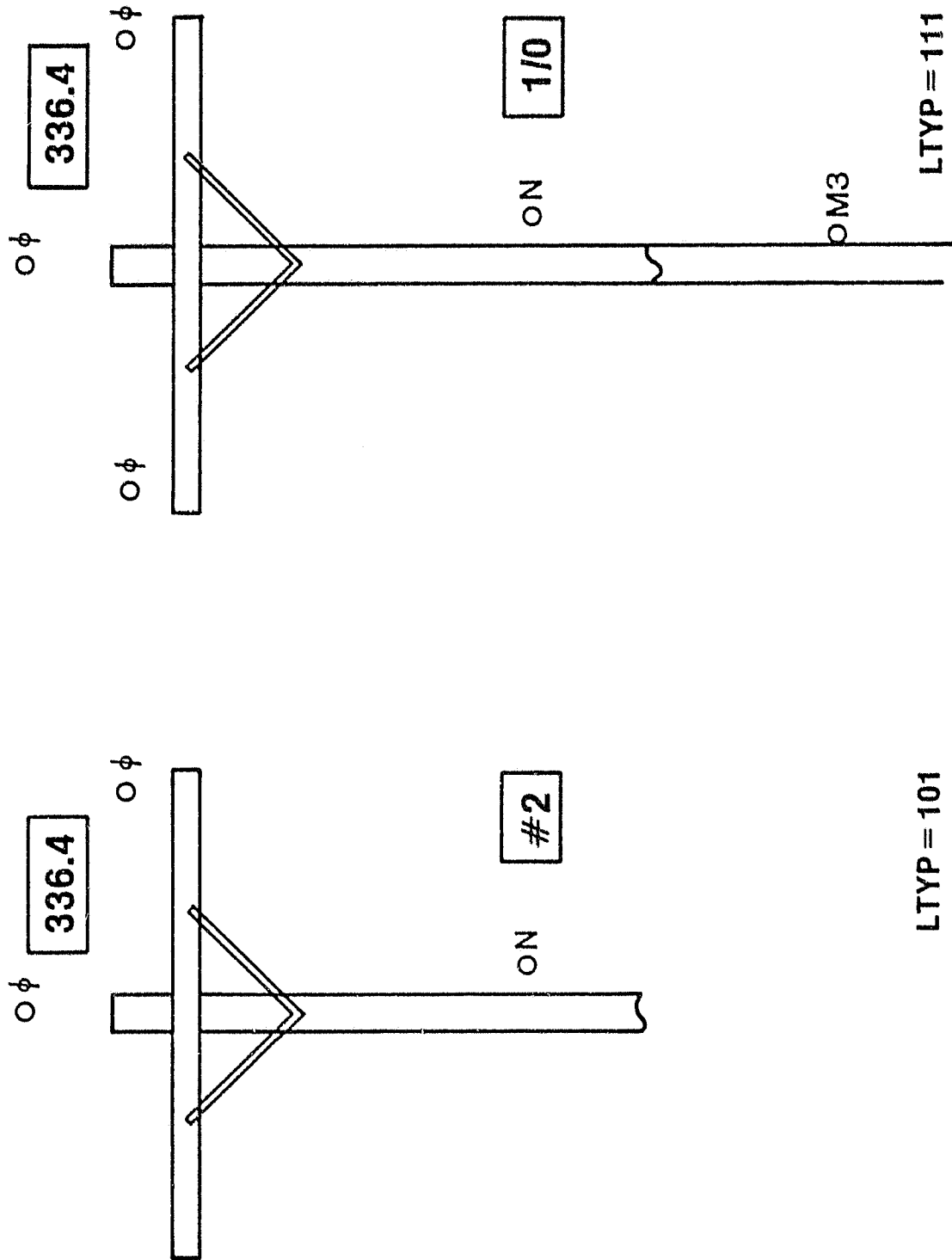


Figure OD-9. Typical Overhead Line Configurations



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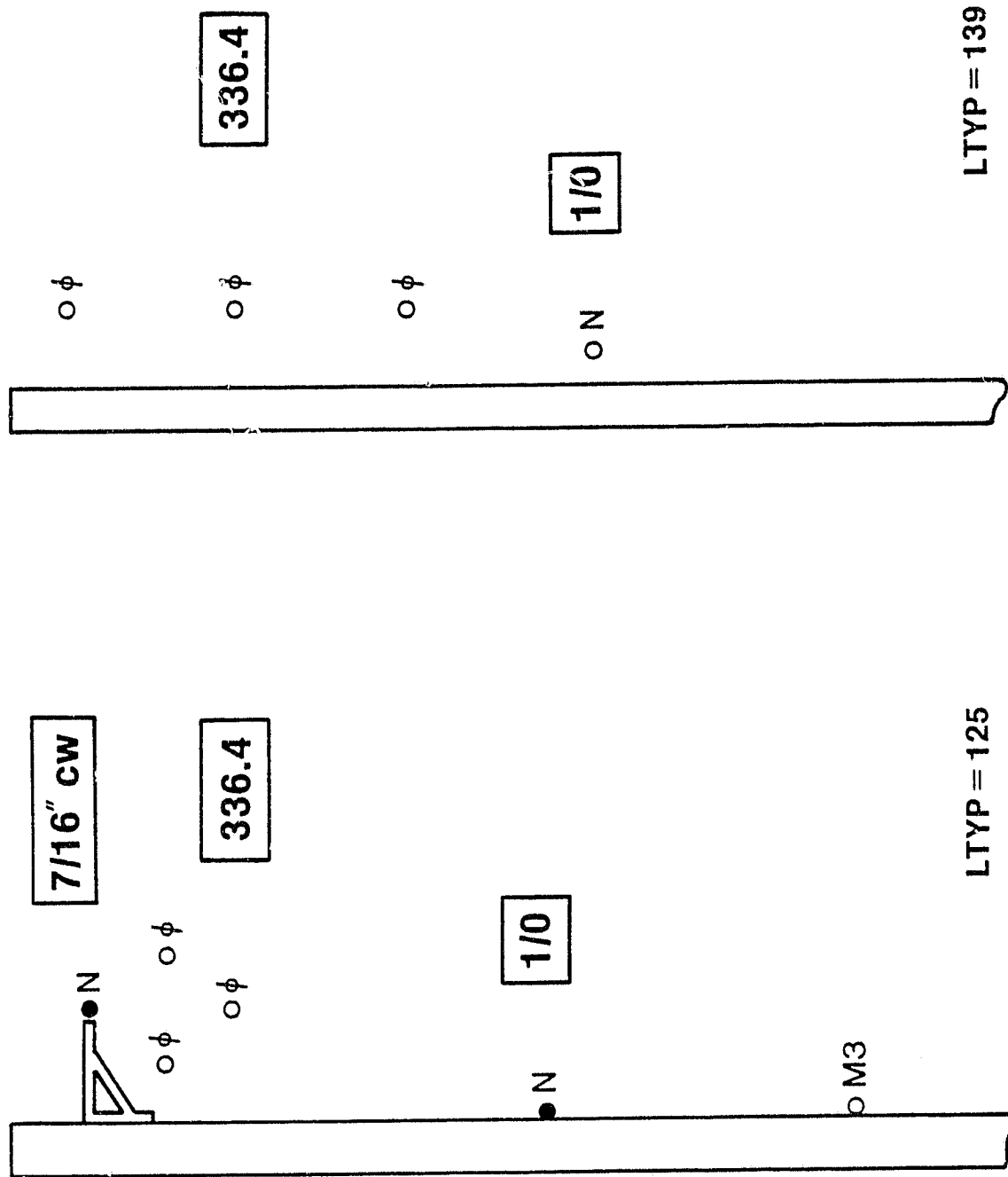


Figure OD-9. Typical Overhead Line Configurations (Cont'd)

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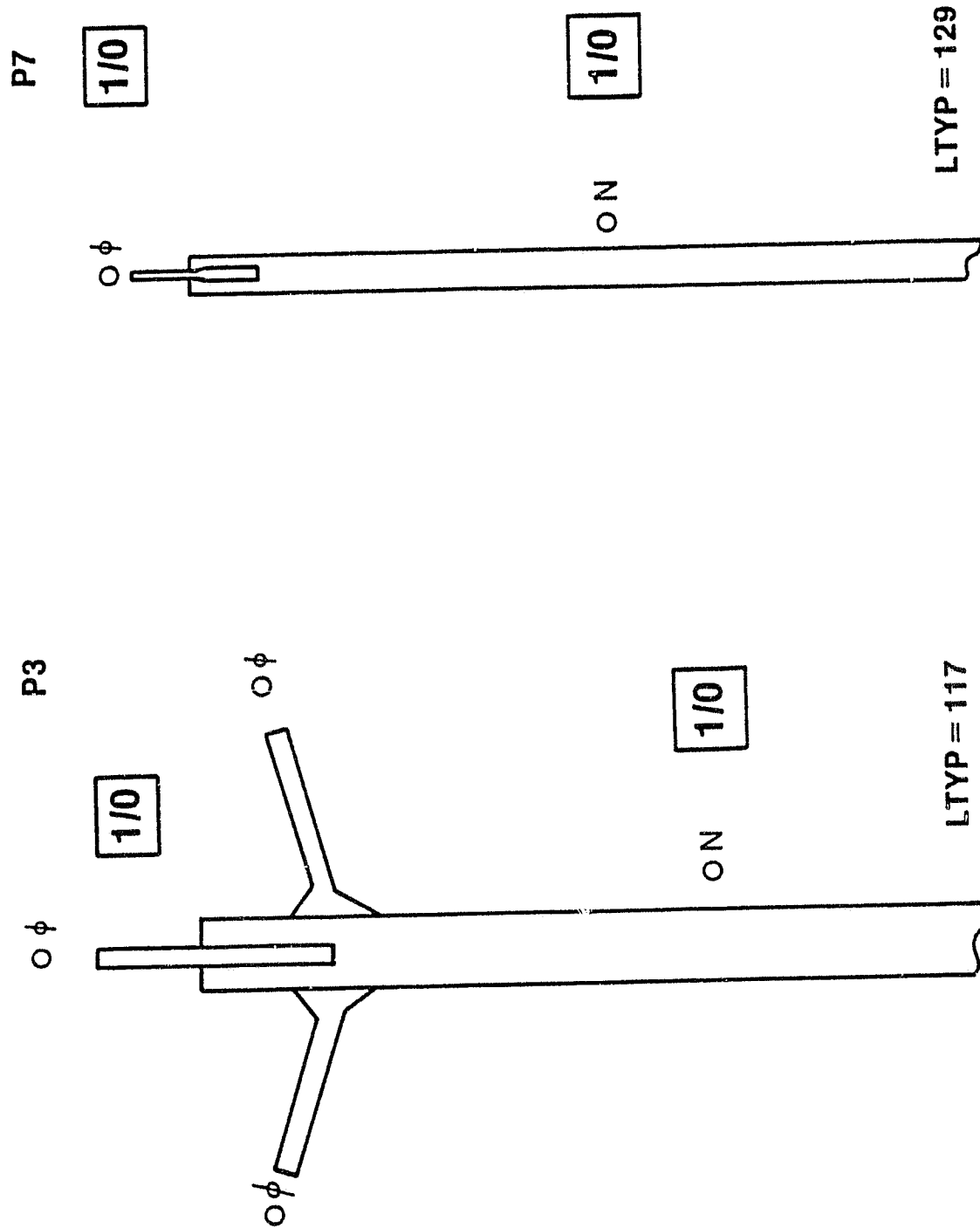


Figure OD-9. Typical Overhead Line Configurations (Cont'd)

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Record Contents

1. Line Number (Sequence Error Check)
2. Node Number
3. Parent Node - 0 for Root Node
4. Leftson Node - 0 if None
5. Rightson Node - 0 if None
6. Line Type Code
7. Length of Node Code (Length x 10)
8. Earth Resistivity Code
9. Transformer Code
10. Phase Code for Transformer Connection
11. Number of Service Drops
12. Primary Load Type Code
13. Neutral-to-Ground Impedance

Continuing with reference to Figure OD-7, Column 8 contains a single-decimal digit representing the earth resistivity code. Figure OD-10 shows a tentative assignment for these codes. Column 9 contains a transformer identification type code which is used by the main network programs to address a data-base file for the transformer parameters. Zero indicates absence of a distribution transformer. Column 10 is the phase connection code which follows the same strategy as for  $1 \leq \text{LTYP} \leq 9$  shown in Figure OD-8. Column 11 contains the number of drops served by the distribution transformer and has been included in anticipation that this parameter may be used to statistically define a total secondary load. Column 12 contains a primary load identification/type number, which if nonzero, is used by the main program to address a data-base file containing

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\*\*\*\*\*

OHMMCODE

\*\*\*\*\*

2	50
4	100
6	200
CODE	OHM-METERS

Figure OD-10. Earth Resistivity Code Assignments

previously specified feeder loads. Column 13 is an integer representation of the user's estimate for the neutral to (true) ground resistance in ohms. This value is used only when operating the main network programs in the modes in which the neutral is not assumed at zero potential.

Figure OD-11 is a slightly modified (to include the annotation on line 1000) listing of such a user prepared network file. This file represents a portion of an actual feeder network. Figure OD-12 is presented for possible interest and shows the "tree" topology of the network defined in Figure OD-11.

(On). Network Computational Procedure

This section will briefly describe the two-stage approach used to compute the response on the network. Before doing so, consider Figure ON-1 which illustrates the input and output of a section, its associated primary load  $Y_L$ , which may be zero, and a termination admittance  $Y_2$  connected to the output. Also implied in this illustration is a transmission line type section, i.e.  $100 \leq LTYP \leq 999$ . This is arbitrary and could be any other type section. Obviously  $Y_2 + Y_L$  represents the total admittance connected to the output terminals of the transmission line. Given the parameters of the transmission line (see Appendix A of the Technical Appendixes Volume) the voltage transfer ratio  $V_{TOPH}$  (matrix) relating the output voltage  $E_2$  to the input voltage  $\vec{E}_1$  (vectors), and the driving-point admittance matrix,  $Y_{IN}$  looking into the input terminals, can be computed. This logically leads to the first of the two stages, a recursive admittance and voltage transfer reduction.

This recursive admittance reduction stage is explained in Figure ON-2, which illustrates the example binary tree network intro-

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R,RUSTAY L/NTWKIN22

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1000	MODE	IPAR	ILSN	IRSN	LTYP	ILCD	IOHM	ITTY	IPHS	NSER	IPRL	INGD
1010	68	0	69	0	111	604	4	0	0	0	0	0
1020	69	68	70	0	125	591	4	25	3	3	0	0
1030	70	69	71	0	125	591	4	0	0	0	0	0
1040	71	70	72	0	111	582	4	0	0	0	0	0
1050	72	71	73	0	115	533	4	10	2	2	0	0
1060	73	72	74	0	111	832	4	10	1	1	0	0
1070	74	73	75	76	111	3066	4	0	0	0	0	0
1080	75	74	0	0	111	622	4	0	0	0	0	0
1090	76	74	77	0	139	610	4	25	1	1	0	0
1100	77	76	78	0	117	2786	4	10	1	1	0	0
1110	78	77	79	0	117	567	4	10	1	3	0	0
1120	79	78	80	0	119	610	4	0	0	0	0	0
1130	80	79	81	0	121	472	4	25	3	4	0	0
1140	81	80	82	0	121	482	4	0	0	0	0	0
1150	82	81	83	86	143	872	4	0	0	0	0	0
1160	83	82	84	88	143	1	4	0	0	0	0	0
1170	84	83	85	0	2	0	4	0	0	0	0	0
1180	85	84	0	0	129	521	4	15	0	2	0	0
1190	86	82	87	0	2	0	4	0	0	0	0	0
1200	87	86	0	0	129	428	4	10	0	1	0	0
1210	88	83	89	0	119	732	4	10	2	1	0	0
1220	89	86	90	0	139	732	4	50	1	3	0	0
1230	90	89	91	0	139	2076	4	0	0	0	0	0
1240	91	90	92	0	121	573	4	25	1	3	0	0
1250	92	91	93	0	119	750	4	10	3	1	0	0
1260	93	92	94	101	119	704	4	0	0	0	0	0
1270	94	93	95	0	3	0	4	0	0	0	0	0
1280	95	94	96	0	131	165	4	0	0	0	0	0
1290	96	95	97	99	131	738	4	0	0	0	0	0
1300	97	96	98	0	135	460	4	0	0	0	0	0
1310	98	97	0	0	129	762	4	50	0	1	0	0
1320	99	96	100	0	135	610	4	25	0	4	0	0
1330	100	99	0	0	129	716	4	10	0	2	0	0
1340	101	93	102	0	119	1097	4	0	0	0	0	0
1350	102	101	103	107	139	1231	4	0	0	0	0	0
1360	103	102	104	0	3	0	4	0	0	0	0	0
1370	104	103	105	0	133	149	4	15	0	1	0	0
1380	105	104	106	0	133	540	4	10	0	1	0	0
1390	106	105	0	0	133	664	4	25	0	1	0	0
1400	107	102	108	0	119	792	4	25	3	2	0	0
1410	108	107	109	111	119	823	4	0	0	0	0	0
1420	109	108	110	0	2	0	4	0	0	0	0	0
1430	110	109	0	0	133	1332	4	15	0	1	0	0
1440	111	108	112	0	139	823	4	10	1	1	0	0
1450	112	111	113	0	139	1594	4	0	0	0	0	0
1460	113	112	114	0	119	762	4	0	0	0	0	0

Figure OD-11. Illustrative User Defined Network File\*

\*Actually representing test network section shown in Figure OD-1  
O-22

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R.RUSTAY1/NTWKIN22

PAGE 2

1470	114	113	115	0	139	1524	4	0	0	0	0	0
1480	115	114	116	0	119	2192	4	0	0	0	0	0
1490	116	115	117	0	139	756	4	0	0	0	0	0
1500	117	116	118	126	119	643	4	0	0	0	0	0
1510	118	117	119	0	3	0	4	0	0	0	0	0
1520	119	118	120	0	129	811	4	10	0	2	0	0
1530	120	119	121	0	129	756	4	0	0	0	0	0
1540	121	120	124	122	129	1198	4	0	0	0	0	0
1550	122	121	123	0	135	640	4	15	0	3	0	0
1560	123	122	0	0	137	2210	4	10	0	2	0	0
1570	124	121	125	138	129	1381	4	0	0	0	0	0
1580	138	124	0	0	135	908	4	25	0	5	0	0
1590	125	124	0	0	135	381	4	10	0	5	0	0
1600	126	117	127	0	141	646	4	25	1	3	0	0
1610	127	126	128	130	119	750	4	0	0	0	0	0
1620	128	127	129	0	1	0	4	0	0	0	0	0
1630	129	128	0	0	133	424	4	10	0	2	0	0
1640	130	127	131	0	139	1524	4	0	0	0	0	0
1650	131	130	132	0	119	1591	4	0	0	0	0	0
1660	132	131	133	135	119	744	4	10	2	1	0	0
1670	133	132	134	0	3	0	4	0	0	0	0	0
1680	134	133	0	0	129	1704	4	10	0	2	0	0
1690	135	132	136	0	119	1490	4	0	0	0	0	0
1700	136	135	137	0	139	610	4	0	0	0	0	0
1710	137	136	0	0	119	2405	4	10	3	1	0	0

Figure OD-11. Illustrative User Defined Network File (Cont'd)

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1470	114	113	115	0	139	1524	4	0	0	0	0	0
1480	115	114	116	0	119	2192	4	0	0	0	0	0
1490	116	115	117	0	139	756	4	0	0	0	0	0
1500	117	116	118	126	119	643	4	0	0	0	0	0
1510	118	117	119	0	3	0	4	0	0	0	0	0
1520	119	118	120	0	129	811	4	10	0	2	0	0
1530	120	119	121	0	129	756	4	0	0	0	0	0
1540	121	120	124	122	129	1198	4	0	0	0	0	0
1550	122	121	123	0	135	640	4	15	0	3	0	0
1560	123	122	0	0	137	2210	4	10	0	2	0	0
1570	124	121	125	138	129	1381	4	0	0	0	0	0
1580	138	124	0	0	135	908	4	25	0	5	0	0
1590	125	124	0	0	135	381	4	10	0	5	0	0
1600	126	117	127	0	141	646	4	25	1	3	0	0
1610	127	126	128	130	119	750	4	0	0	0	0	0
1620	128	127	129	0	1	0	4	0	0	0	0	0
1630	129	128	0	0	133	424	4	10	0	2	0	0
1640	130	127	131	0	139	1524	4	0	0	0	0	0
1650	131	130	132	0	119	1591	4	0	0	0	0	0
1660	132	131	133	135	119	744	4	10	2	1	0	0
1670	133	132	134	0	3	0	4	0	0	0	0	0
1680	134	133	0	0	129	1704	4	10	0	2	0	0
1690	135	132	136	0	119	1490	4	0	0	0	0	0
1700	136	135	137	0	139	610	4	0	0	0	0	0
1710	137	136	0	0	119	2405	4	10	3	1	0	0

Figure OD-11. Illustrative User Defined Network File (Cont'd)



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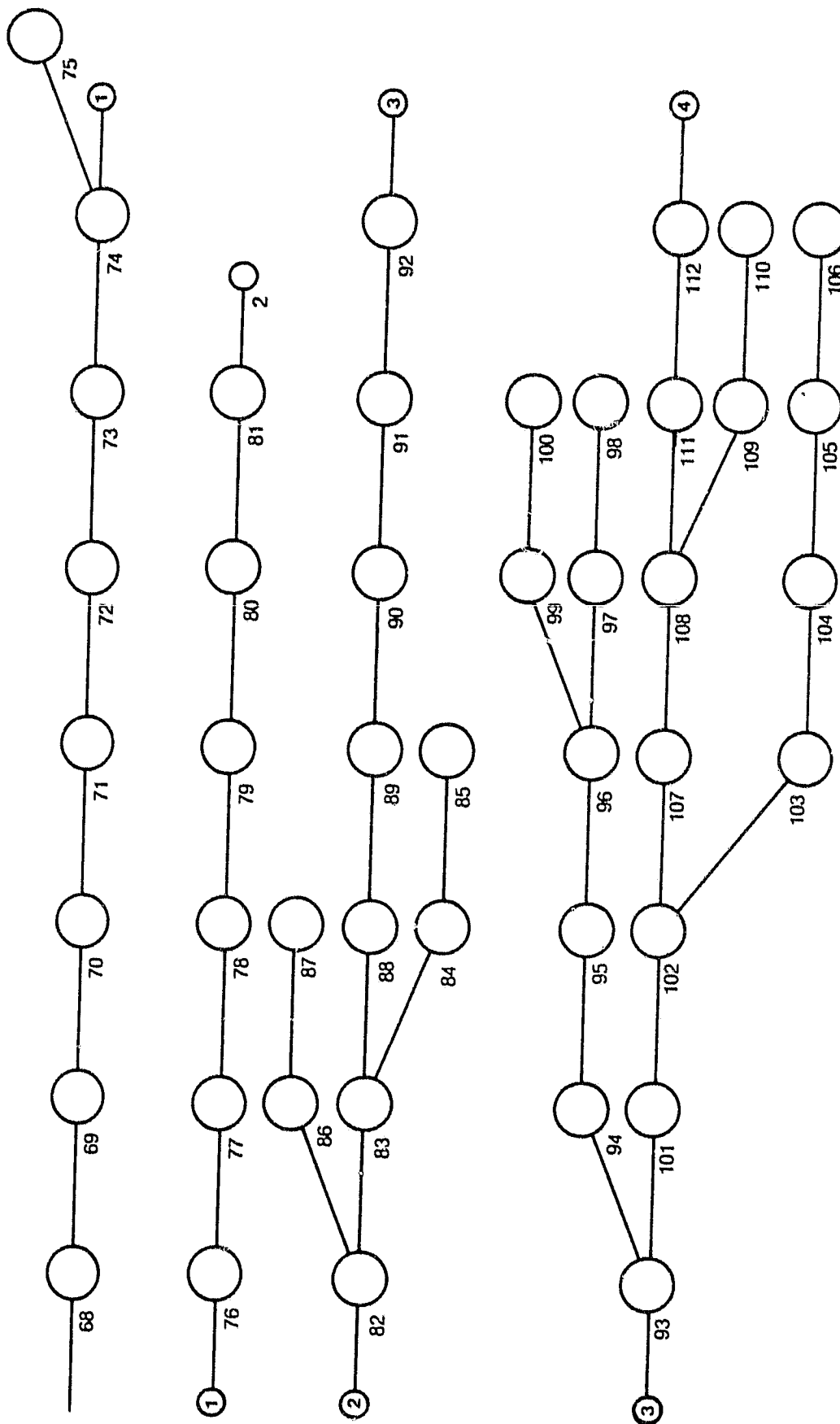


Figure OD-12. Tree "Topology" for Network Defined in Figure OD-11

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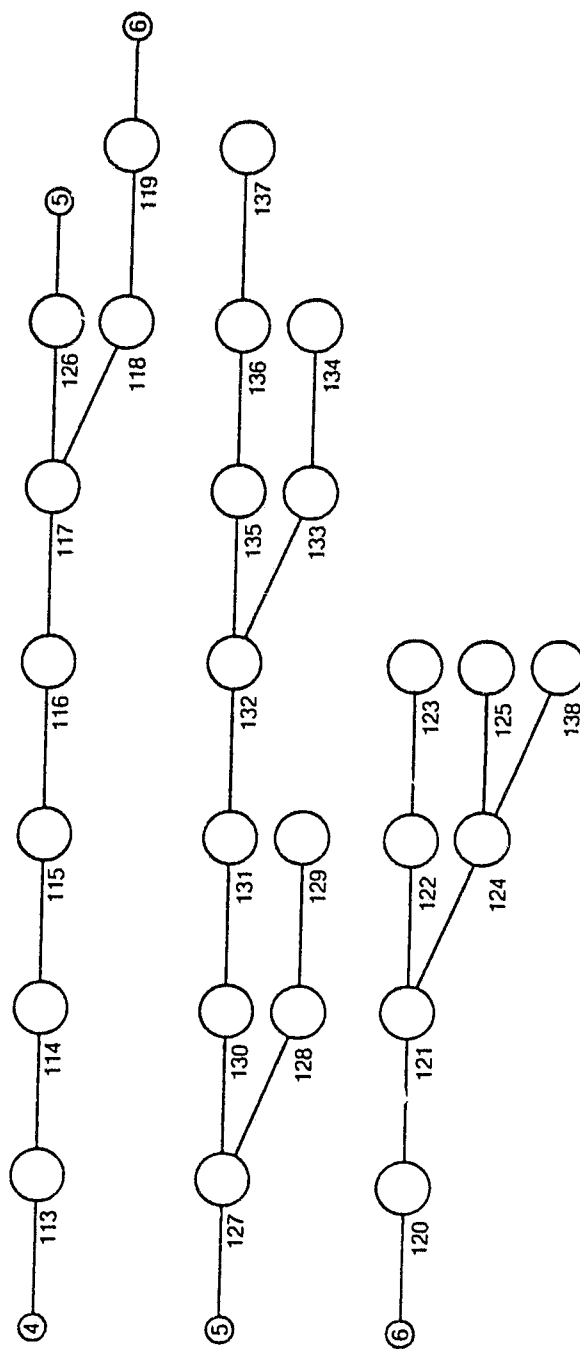
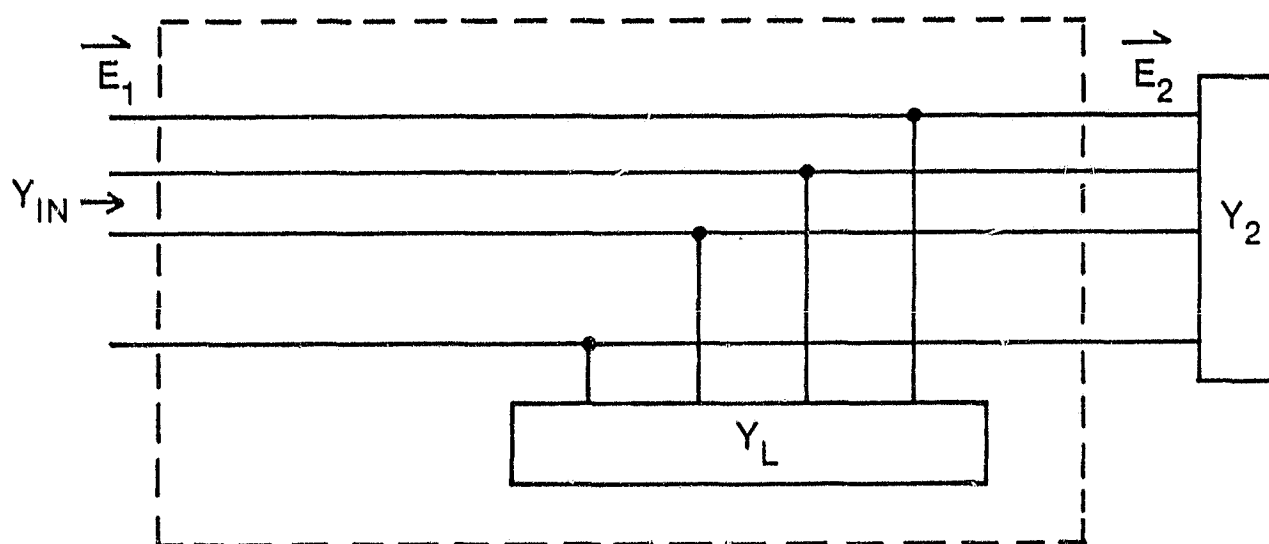


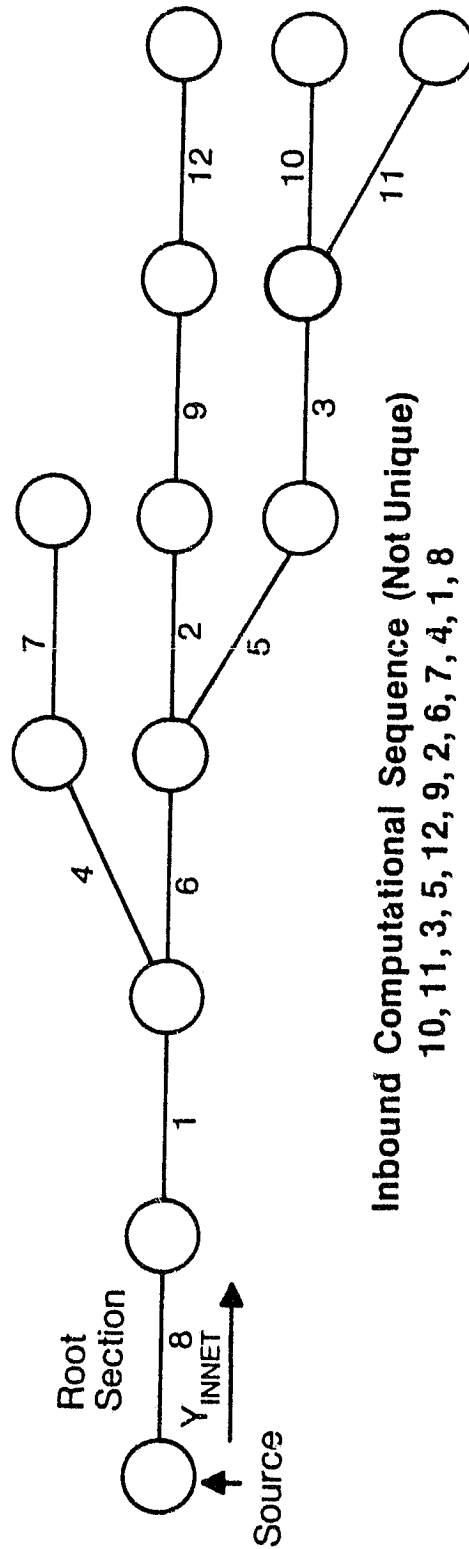
Figure OD-12. Tree "Topology" for Network Defined in Figure OD-11 (Cont'd)

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$$\vec{E}_2 = V_{TOPH} * \vec{E}_1$$

Figure ON-1. Section Voltage Transfer Ratio and Input Driving-Point Admittance



Inbound Computational Sequence (Not Unique)

10, 11, 3, 5, 12, 9, 2, 6, 7, 4, 1, 8

End Result of Admittance Reduction Is the Input Admittance,  $Y_{INNET}$ , for Tree Network. In Addition, the Voltage Transfer Matrix VOTPH, Input Admittance  $Y_{IN}$  Etc. Are Saved on a File for Each Section as It Is Computed.

Computer Program NTWKERSI  
Performs this Admittance Reduction

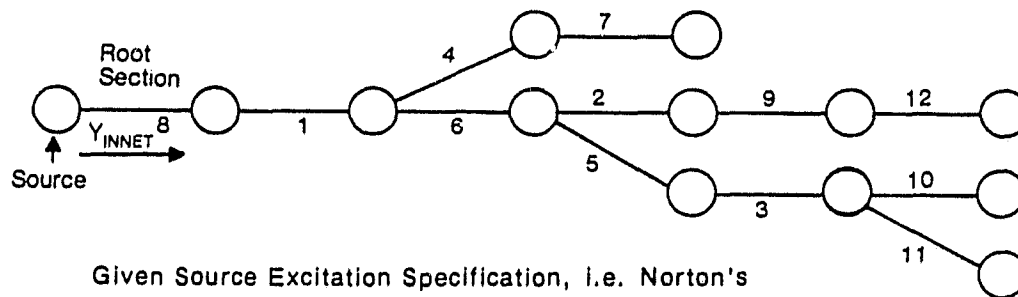
Figure ON-2. Illustrative Binary Tree Network Admittance Reduction

duced earlier. Utilizing the section parent, left son, and right son entries contained in the user generated network file, a sequencing algorithm develops a computational sequence, not unique, such as shown in Figure ON-2. The idea is simple. Progressing inbound from a terminus node, it is evident that recursively applying, in the sequence shown, the admittance transformation, using as appropriate, some amount (usually small) of temporary core store, the input driving-point admittance and voltage transfer ratio for every section can be determined, including the driving-point admittance presented to the source by the network, i.e. associated with the root section. All of these admittances and voltage transfer ratios (and other useful matrixes) are saved in a file as each section is computed. This first-stage procedure is accomplished in main program NTWKERS1.

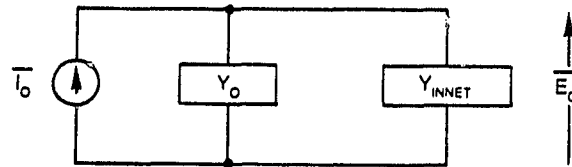
The second stage associated with the calculation of voltages, currents, and power at each section, begins with the determination of the voltage at the input to the root section by utilizing a user specified source, usually a Norton's Equivalent Source in vector-matrix form. Again using the section and parent entries of the user specified network file, a direct path sequence is established from a user specified section (where he desires a response calculation) to the first-encountered section (the root section for the first time) whose input voltage has been previously determined. This path sequence is saved in a push-down stack. Then using the saved voltage transfer ratios, the voltages for each section along the path are computed in the logical sequence saved in the stack. As each voltage is computed, it is saved in the same file for possible

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subsequent runs. This procedure is summarized in Figure ON-3. In addition to the section voltages, other quantities such as  $Y_N$  and  $Y_{OUT}$  (see Figure ON-4) are computed and saved. The procedures of this second stage are accomplished by the main network program NTWKANS1.



Given Source Excitation Specification, i.e. Norton's  
 $\bar{I}_0$  Source Current Vector     $Y_0$  Source Admittance Matrix  
 Compute Drive Voltage  $\bar{E}_0$  Vector



Then Use Saved Data Such as the Voltage Transfer Ratio Matrices to Compute Voltages (and Then Currents) in Outbound Direction to Desired/Specified Section. At All Sections on the Path, All Voltage, Currents and Other Quantities Are Saved.

**Computer Program NTWKANS1  
Performs Signal Propagation Calculations**

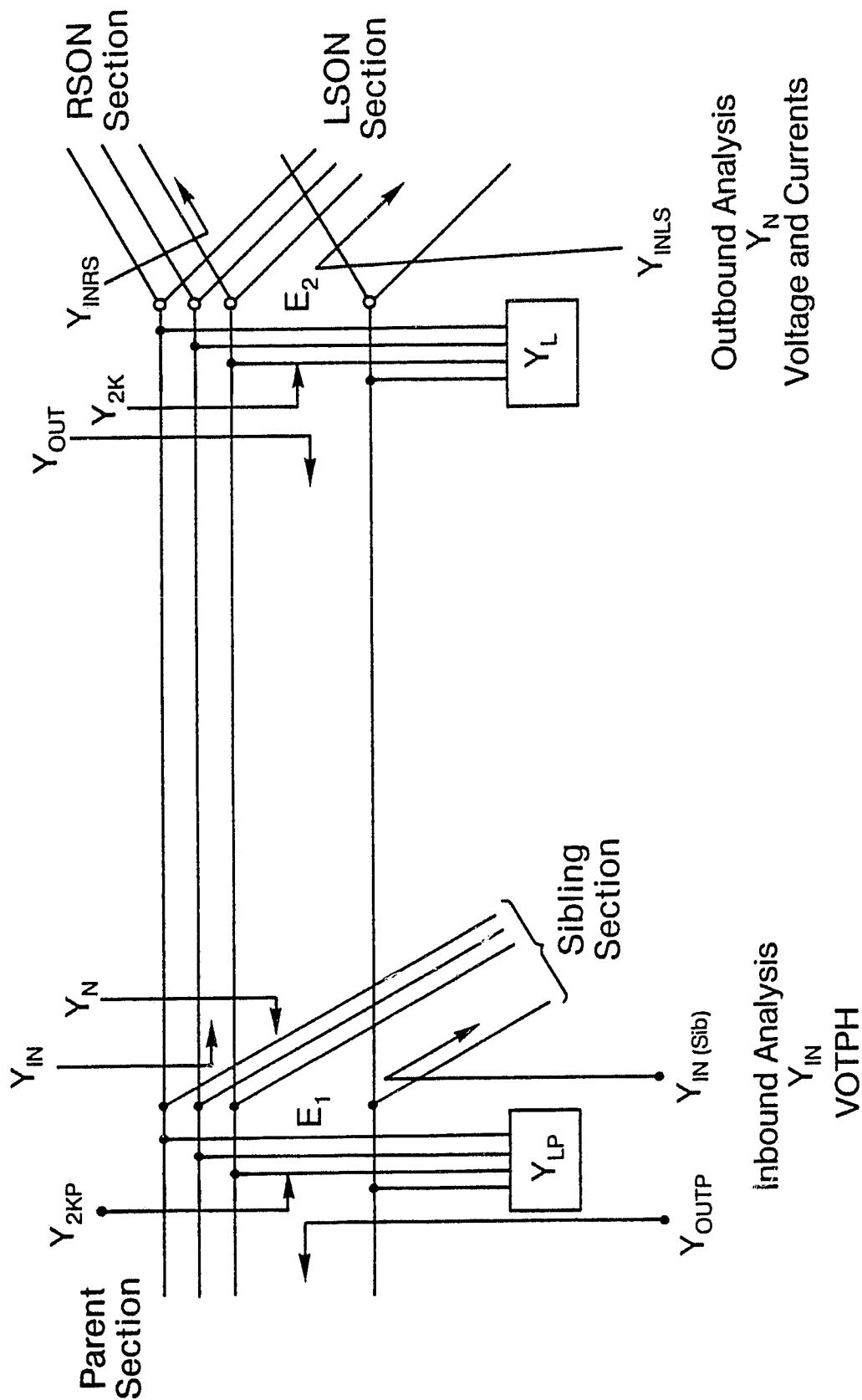
Figure ON-3. Signal Propagation Calculation in Illustrative Tree Network

(Ot). Computer Program Interrelationships

The interrelationship between the various programs in the DIFNAP system is shown in Figure Ot-1. The two main programs are NTWKERS1 and NTWKANS1.

Program NTWKERS1 takes the network description from data file DNWKINIj and uses it to compute driving point admittance matrices and voltage transfer ratio matrices. The procedure used is to

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Outbound Analysis  
 $Y_N$   
Voltage and Currents

Inbound Analysis  
 $Y_{IN}$   
VOTPH

The Above and Other Vectors and Matrices Are Saved  
in a File for Future Use

Figure 0N-4. Single Section Detail

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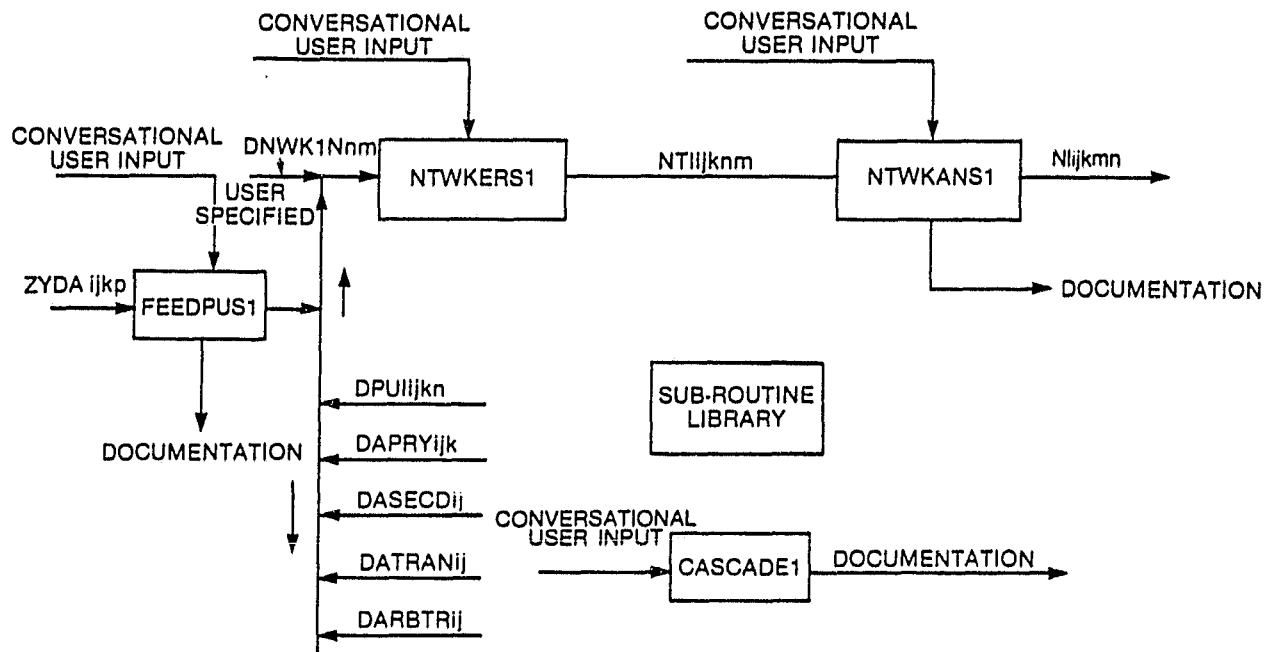


Figure OT-1. The DIFNAP System of Programs



start at the terminal sections and work inwards towards the root of the network. The program uses the following data base files:

DPUlijkn - parameter of lines used  
DAPRYijk - primary load file  
ASCII RBTRDAIA - for single phase ratio bank transformer\*  
ASCII TRANFILE - for distribution transformers\*\*

Brief descriptions of the data base files are provided in the User Handbook (Volume-4). The data file DPUlijkn is generated from the ZYDAijkp data file using the FEEDPUSl program. The ZYDAijkp data files are, in turn, generated using the DISEM7S1 program as described in the User Handbook. The primary output of NTWKERSl is a random binary data file NTlijknm.

Program NTWKANS1 takes the random binary data file NTlijknm generated by NTWKERS1 as its input and computes voltage and currents at specific points on the network. The user specifies the source properties as a part of the conversational input. The output is placed in an ASCII file Nlijkmn. In addition, the NTlijknm file is updated so that the same network is analyzed with the same source. At another time, computations already made need not be repeated.

In addition, the DIFNAP system also contains a program, CASCADE1, which can be used for the computation of a non-branched cascade of sections.

Descriptions of the conversational input to the DIFNAP programs are given in the User Handbook.

\* See listing of NTWKERS4 (beginning with line 7250) in Volume 4.

\*\* See listings of TRANADS4, TRANFILE in Volume 4.